NASA TECHNICAL MEMORANDUM

NASA TM X- 53447

April 20, 1966

NASA TM X- 53447

N66 26281 (ACCESSION NUMBER) _____ (THRU)

167 (PAGES) 1 (CODE)

TMX-53447 (NASA CR OR TMX OR AD NUMBER) 15 (CATEGORY)

FACILITY FORM

# JOINING OF NICKEL AND NICKEL-BASE ALLOYS

By J. J. Vagi, R. E. Monroe, R. M. Evans, and D. C. Martin

Prepared Under the Supervision of the
Research Branch, Redstone Scientific Information Center
Directorate of Research and Development
U. S. Army Missile Command
Redstone Arsenal, Alabama

NASA

*George C. Marshall Space Flight Center, Huntsville, Alabama*

GPO PRICE $ _____

CFSTI PRICE(S) $ _____

Hard copy (HC) 5.00

Microfiche (MF) 1.00

ff 653 July 65

TECHNICAL MEMORANDUM X-53447

# JOINING OF NICKEL AND NICKEL-BASE ALLOYS

By

J. J. Vagi, R. E. Monroe, R. M. Evans, and D. C. Martin*

ABSTRACT

26281

The state of the art of the joining of nickel and nickel-base alloys that contain at least 50 per cent nickel is reviewed. This report covers joining by welding, brazing, and soldering. Joining preparations, specific joining processes, joining dissimilar metals, and joint quality are discussed.

*Principal Investigators, Battelle Memorial Institute, Contract No. DA-01-021-AMC-11651(Z)

NASA-GEORGE C. MARSHALL SPACE FLIGHT CENTER

# PREFACE

This report is one of a series of state-of-the-art reports being prepared by Battelle Memorial Institute, Columbus, Ohio, under Contract No. DA-01-021-AMC-11651(Z), in the general field of materials fabrication.

This report reviews practices for joining nickel and nickel-base alloys that contain at least 50 per cent nickel. Discussions are presented to provide

(1) Information on joining preparations

(2) Information on joining processes

(3) Information on joint quality.

Techniques and special considerations that are normally followed when joining these alloys are described.

Information in this report was obtained from equipment manufacturers, nickel producers, technical publications, reports from Government contracts, and from interviews with engineers employed by major fabricators of nickel-base alloys. Data from reports and memoranda issued by the Defense Metals Information Center also are used. Assistance afforded by previous programs has also helped in the preparation of this report. The literature search for this program began with 1962, since DMIC Report 181 issued in 1962 covered the joining of nickel-base alloys up to that time.

In accumulating the information necessary to prepare this report, the following sources within Battelle were searched, covering the period January, 1962, to the present:

Defense Metals Information Center
Main Library
Slavic Library
Welding Journal Indexes (1960 to present).

Information also was obtained from sources outside of Battelle, viz., the Redstone Scientific Information Center and the Defense Documentation Center.

NASA-GEORGE C. MARSHALL SPACE FLIGHT CENTER

TECHNICAL MEMORANDUM X-53447

# JOINING OF NICKEL AND NICKEL-BASE ALLOYS

By

J. J. Vagi, R. E. Monroe, R. M. Evans, and D. C. Martin

Prepared for

Manufacturing Engineering Laboratory

In Cooperation with

Technology Utilization Office

Under the Supervision of

Redstone Scientific Information Center
U. S. Army Missile Command
Redstone Arsenal, Alabama
MSFC Order No. H-76715
Report No. RSIC-484

Subcontracted to

Battelle Memorial Institute
505 King Avenue
Columbus, Ohio
Contract No. DA-01-021-AMC-11651(Z)

Personal contacts also were made by visit or telephone with the following individuals and organizations:

Richard E. Avery
G. L. Lansdal
Huntington Alloy Products Division
The International Nickel Company, Inc.
Huntington, West Virginia

Howard Cary
Hobart Brothers
Hobart Square
Troy, Ohio

D. J. Collins
The Martin Company
Orlando, Florida

Joice O. Cox, Jr., Chief
Victor H. Pagano
Materials Laboratory
Headquarters
United States Army Tank-Automotive Center
Warren, Michigan

A. M. Edwards
Union Carbide Corporation
Stellite Division
General Office
Kokomo, Indiana

R. S. Emlong
Astro Metallurgical Corporation
3225 Lincoln Way West
Wooster, Ohio

Edward A. Fenton
Technical Director
American Welding Society, Inc.
United Engineering Center
345 East 47th Street
New York, New York

Stanley P. Filipski
Linde Division
Union Carbide Corporation
Newark, New Jersey

W. A. Hutton
Production Information, Building 700-N-33
Flight Propulsion Laboratory Dept.
General Electric Company
Cincinnati, Ohio

K. C. Linepensel
Technical Information Administrator
Union Carbide Corporation
Linde Division
P. O. Box 2819
686 Frelinghuysen Avenue
Newark, New Jersey

George Mandel, Assistant Chief
Technical Information Division
National Aeronautics and Space Administration
Lewis Research Center
21000 Brookpark Road
Cleveland, Ohio

R. Meisenbach
AMF Beaird, Inc.
P. O. Box 1115
Shreveport, Louisiana

John J. Mullins
Hamilton Standard Division
United Aircraft Corporation
Windsor Locks, Connecticut

Edward J. Regan
Public Relations
McDonnell Aircraft Corp.
Box 516
St. Louis, Missouri

Chris Sampson, Jr.
The American Welding and
Manufacturing Co.
Warren, Ohio

A. M. Scroogs
Boeing Airplane Company
Seattle, Washington

Gerald M. Slaughter
Oak Ridge National Laboratory
Oak Ridge, Tennessee

Doyle F. Smee, Manager
Corporate Information Services
Allegheny Ludlum Steel
Corporation
Executive and General Offices
20th Floor Oliver Building
Pittsburgh, Pennsylvania

Mr. Sumner Smith
Menasco Manufacturing Company
Burbank, California

Floyd L. Thompson
Director
Langley Research Center
Langley Station
Hampton, Virginia

Fred W. Vogel
Editor
Modern Machine Shop
431 Main Street
Cincinnait, Ohio

K. N. Thompson, Editor
Welding and Metal Fabrication
Dorset House
Stamford Street
London, SE1, England

The authors wish to thank each of these individuals and their organizations for contributions. They also wish to thank Vernon W. Ellzey and Albert G. Imgram of Battelle; Project Technical Co-ordinators, and Walter H. Veazie, Battelle Information Specialist, for their assistance during this program.

TABLE OF CONTENTS

TABLE OF CONTENTS
(Continued)

## LIST OF ILLUSTRATIONS

## LIST OF ILLUSTRATIONS
(Continued)

LIST OF ILLUSTRATIONS
(Continued)

## LIST OF ILLUSTRATIONS
(Continued)

## LIST OF TABLES

LIST OF TABLES
(Continued)

# TECHNICAL MEMORANDUM X-53447

## JOINING OF NICKEL AND NICKEL-BASE ALLOYS


### SUMMARY

Nickel and nickel-base alloys are amenable to joining with many of the familiar joining processes. Some new joining processes also have been used successfully. In general, conventional joining procedures are used with only slight required modifications, depending on the particular alloy to be welded. However, some special precautions must be taken. Harmful materials must be removed from the joint or surrounding areas or they may damage the weld and the nearby heated parent metal. Some high-strength age-hardenable alloys are prone to cracking in or near joint areas, unless the material is in the proper condition of heat treatment prior to joining operations. Foreign material and flux residues left from joining operations can cause trouble in subsequent service if not removed.

Procedures for joining these alloys have been developed that eliminate or minimize the usual difficulties that have been experienced. When proper procedures are employed, joining of nickel and nickel-base alloys can be performed satisfactorily.


### INTRODUCTION

This report summarizes available information on joining of nickel and nickel-base alloys. Discussions are presented in three main sections: "Joining Preparation", "Joining Processes", and "Joint Quality". Considerations that are applicable to all nickel alloys or to large groups of nickel alloys are described in the first section. Information on product materials, joint design, preweld and postweld cleaning, welding fixtures and tooling, and other factors to consider before joining also are included in the first section. Individual joining processes, dissimilar metal joining, and special considerations to be taken when joining the various alloys are described in the second section. Inspection techniques, defects, and repair procedures are described in the third section.

Joining of four types of nickel-base materials is described in this report:

(1) High-purity nickel
(2) Solid-solution-hardening nickel-base alloys
(3) Precipitation-hardening nickel-base alloys
(4) Dispersion-hardening nickel-base alloys.

The high-nickel and solid-solution-hardening alloys are widely used in chemical containers and piping. These materials have excellent corrosion and oxidation resistance, and retain useful strength at elevated temperatures. The precipitation-hardening alloys have good elevated-temperature properties. They are important in many aerospace applications. Dispersion-hardening nickel also is used for elevated-temperature service.

The many uses of nickel and nickel-base alloys arise from certain inherently desirable properties:

(1) Corrosion resistance at room and elevated temperature
(2) Oxidation resistance at elevated temperature
(3) Good mechanical properties at cryogenic, room, and elevated temperature
(4) Easy fabrication.

Joining operations are important in fabricating all of the nickel alloys into useful products that possess these properties in combinations suitable for the particular service conditions.

When joining nickel and nickel-base alloys, the factors that are basic to successful joining operations include, in broad terms: (1) the material to be joined, (2) the joining process to be used, and (3) inspections and repair procedures. These factors are described in detail in this report.

## JOINING PREPARATION

The selections of materials, equipment, component designs, and processes are all important steps before starting a joining operation. The joining specialist should be familiar with the basic properties of

the materials he will be joining. Necessary equipment for all processing associated with joining must be available. Joint designs, cleaning procedures, and heat-treating operations must be considered. Also, some planning must be done to control distortion and to anticipate required post-joining operations. Selection of the joining process to be used also occurs at this time.

Those portions of these selection criteria that are most important in the joining of nickel-base alloys are discussed in the following sections.

## MATERIALS

When planning joining operations for nickel and nickel-base alloys a good understanding of the materials and of their behavior during joining operations is needed. Several types of materials may be involved in joining operations. The particular alloy to be joined, metals that are added to the joint, and materials that are used to protect the heated metals must be considered. These materials are:

(1) Base Metals – The material being joined usually is called the "base metal", "parent metal", or "base plate". Nickel and nickel-base-alloy base metals range in thicknesses from foils to plates that are several inches thick and in sizes from microminiature electronic components to railroad-tank cars. Often pieces of base-metal materials used in joining a part are not an integral part of the completed product. Starting and runoff tabs are typical examples. Such parts assist the welding operation but are removed when they are no longer needed.

(2) Filler Metals – Filler metals are those metals that are added to complete a joint. For fusion welding, filler metals include coated welding electrodes, coiled wire on spools, and short lengths of wire or strips sheared or machined from the parent-metal sheet or plate. For brazing, filler metals may or may not contain nickel and include foil, wire, powder, and powder-flux pastes. For soldering, filler metals include wire, paste, and molten-solder baths. Filler metals as such are seldom used with the following processes: resistance spot and seam welding, roll resistance spot welding, and flash welding.

When selecting filler metals for joining nickel and nickel-base alloys, it is important to consider the compatibility of the filler metal with service requirements and subsequent processing. Corrosion resistance and mechanical properties

of the completed joint, for example, may differ considerably from the parent metal. Filler metals also should be compatible with subsequent heat-treating requirements. Normally, they are expected to provide properties that equal or exceed the base-metal properties in the finished weldment.

(3) Shielding Gases and Fluxes – Several gases are used for shielding nickel and nickel-base alloys during joining. Argon, helium, argon-helium mixtures, and hydrogen are the most common ones. Argon-1 per cent oxygen mixtures also have been used for welding a limited number of alloys (Ref. 1). When gases are used for joining, special high-purity grades are recommended; these high-purity grades are available commercially. When using these gases in welding, brazing, or other joining operations, the main objective is to protect the hot weld metal, base metal, and electrodes from being contaminated by the surrounding atmosphere. Oxygen, nitrogen, water vapor, and other constituents of air and shop atmospheres can be harmful to the weldment. Argon and helium also are used to prevent contamination of tungsten electrodes and filler wires used with the gas-metal-arc welding processes.

Fluxes are used to help protect the weld metals from contamination. They function by providing gases and slag coverings, or by blanketing the heated areas with protective films. They are provided in the form of electrode coverings and loose powders for fusion welding, and as powders and pastes for soldering and brazing operations.

Nickel and Nickel-Base Alloys. For this report, nickel and nickel-base alloys are divided into four types:

(1) High-purity and high-nickel alloys
(2) Solid-solution hardening nickel-base alloys
(3) Precipitation-hardening nickel-base alloys
(4) Dispersion-hardening nickel-base alloys.

Each type of alloy has different characteristics than the other types. A brief description of each of these alloy types is as follows.

High-Purity Nickel Alloys. The high-purity nickel alloys generally contain more than about 95 per cent nickel. Mechanical properties vary, depending on their hot- or cold-worked condition. Cold working, however, increases hardness and strength; these properties may be altered by heat treatment of cold-worked material. In general, heat treatment does not improve the properties of nickel, however. Permanickel is an exception; it is an age-hardenable alloy.

Solid-Solution-Hardening Alloys. These alloys include the older, less heat-resistant, but highly corrosion-resistant nickel-base alloys. They are not usually considered heat treatable. Heat treatment may be used to soften them after cold-working operations.

Precipitation-Hardening Nickel-Base Alloys. These alloys are strengthened by heat treatment. They were developed to meet needs for alloys that can operate at high temperatures under high stress. Practically all of them contain aluminum and titanium, and strengthening occurs due to precipitation of a nickel-aluminum-titanium phase, $Ni_3(Al, Ti)$, known as gamma prime ($\gamma'$). The usual heat treatment is a two-step procedure – solution treating and aging.

Dispersion-Hardening Nickel-Base Alloys (TD Nickel). Thoria-dispersion-strengthened nickel (TD nickel) contains about 2 volume per cent thoria (thorium oxide) and the balance nickel. Submicron-size thoria particles are uniformly dispersed within the nickel matrix by a chemical process. This type of dispersion significantly increases the tensile strength of nickel at elevated temperatures.

The more familiar nickel-base alloys and their uses are given in Table I (Refs. 2, 3, 4, 5). Individual alloys within each major type may have somewhat differing characteristics as illustrated by the varying uses of the alloys.

It is beyond the scope of this report to cover all of the effects of alloying elements in nickel and nickel-base alloys, but it is useful to consider the effects of major alloying elements on weldability. A knowledge of the effects of about 25 elements is necessary for an understanding of the joining characteristics of nickel-base alloys. A summary of the effects of these elements on joining is shown in Table II and discussed in the following paragraphs (Refs. 6-8).

TABLE I. NICKEL AND NICKEL-BASE ALLOYS – CHEMICAL COMPOSITION AND USES (REFS. 2, 3, 4, 5)

| Trademark | Compositions, weight per cent | | | | | | | | | | | | Uses |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Ni[a] | C | Cr | Mo | Fe | Co | Cu | Al | Ti | Cb[b] | Mn | Si | Others | |
| **Commercially Pure and High-Nickel Alloys** | | | | | | | | | | | | | | |
| Nickel 200 | 99.5 | 0.06 | -- | -- | 0.15 | -- | 0.05 | -- | -- | -- | 0.25 | 0.05 | -- | Rocket motors, chemical shipping drums |
| Nickel 201 | 99.5 | 0.01 | -- | -- | 0.15 | -- | 0.05 | -- | -- | -- | 0.20 | 0.05 | -- | Caustic evaporators, combustion boats |
| Nickel 204 | 95.2 | 0.06 | -- | -- | 0.05 | 4.50 | 0.02 | -- | -- | -- | 0.20 | 0.02 | -- | Sonar equipment, ultrasonic cleaning and welding equipment |
| Nickel 205 | 99.5 | 0.06 | -- | -- | 0.10 | -- | 0.05 | -- | 0.02 | -- | 0.20 | 0.05 | 0.04 Mg | Electronic component, wires, rods pins |
| Nickel 211 | 95.0 | 0.10 | -- | -- | 0.05 | -- | 0.03 | -- | -- | -- | 4.75 | 0.05 | -- | Sparkplug electrodes, electron-tube grid wires |
| Nickel 212 | 97.7 | 0.10 | -- | -- | 0.05 | -- | 0.03 | -- | -- | -- | 2.00 | 0.05 | -- | Lamp-support wires, furnace lead wires |
| Nickel 220 | 99.5 | 0.06 | -- | -- | 0.05 | -- | 0.03 | -- | 0.02 | -- | 0.12 | 0.03 | 0.04 Mg | Electron-tube cathodes |
| Nickel 225 | 99.5 | 0.06 | -- | -- | 0.05 | -- | 0.03 | -- | 0.02 | -- | 0.13 | 0.20 | 0.04 Mg | Electron-tube cathodes |
| Nickel 230 | 99.5 | 0.09 | -- | -- | 0.05 | -- | 0.01 | -- | 0.003 | -- | 0.10 | 0.03 | 0.06 Mg | Electron-tube cathodes |
| Nickel 233 | 99.5 | 0.09 | -- | -- | 0.05 | -- | 0.03 | -- | 0.003 | -- | 0.18 | 0.03 | 0.07 Mg | Electron-tube plates, cathodes, and structural components |
| Nickel 270 | 99.97 | 0.02 | Trace | -- | Trace | -- | Trace | -- | -- | -- | Trace | Trace | -- | Heat exchangers, electron-tube components |
| **Alloys Hardened Principally by Solid Solution** | | | | | | | | | | | | | | |
| Monel 400 | 66.0 | 0.12 | -- | -- | 1.35 | -- | 31.5 | -- | -- | -- | 0.90 | 0.15 | -- | Marine and chemical heat exchangers |
| Monel 401 | 44.5 | 0.03 | -- | -- | 0.20 | 0.50 | 53.0 | -- | -- | -- | 1.70 | 0.01 | -- | Electronic components |
| Monel 402 | 58.0 | 0.12 | -- | -- | 1.20 | -- | 40.0 | -- | -- | -- | 0.90 | 0.10 | -- | Pickling tanks for steel and copper |
| Monel 403 | 57.5 | 0.12 | -- | -- | 0.50 | -- | 40.0 | -- | -- | -- | 1.80 | 0.25 | -- | Gasoline and fresh-water tanks, minesweeper fittings |
| Monel 404 | 55.0 | 0.06 | -- | -- | 0.05 | -- | 44.0 | 0.02 | -- | -- | 0.01 | 0.02 | -- | Wave guides, transistor capsules, metal-to-ceramic seals |
| Monel R-405 | 66.0 | 0.18 | -- | -- | 1.35 | -- | 31.5 | -- | -- | -- | 0.90 | 0.15 | -- | Free-machining screw-machine products |
| Monel 406 | 84.0 | 0.12 | -- | -- | 1.35 | -- | 13.0 | -- | -- | -- | 0.90 | 0.15 | -- | Hot-water tanks |
| Nimonic 75 | 71-78 | 0.08-0.15 | 18-21 | -- | 5.0 | -- | 0.5 | -- | 0.2-0.6 | -- | 1.0 | 1.0 | -- | Combustion cans |
| | 76 | 0.12 | 20 | -- | 2.4 | -- | -- | 0.06 | 0.4 | -- | 0.4 | 0.6 | -- | |
| Illium R | 68 | 0.05 | 21.0 | 5.0 | 1.0 | -- | 3.0 | -- | -- | -- | 1.25 | 0.70 | -- | -- |
| Illium G | 56 | 0.20 | 22.5 | 6.4 | 6.5 | -- | 6.5 | -- | -- | -- | 1.25 | 0.65 | -- | -- |
| Hastelloy B | Bal | 0.05-0.12 | 1.0 | 26-30 | 4.0-7.0 | 2.5 | -- | -- | -- | -- | 1.0 | 1.0[c] | 0.2-0.6V | Corrosion-resistant alloy |
| | 61 | 0.10 | 1.0 | 28 | 5.0 | -- | -- | -- | -- | -- | 0.8 | 0.7 | -- | |
| Hastelloy C | Bal | 0.08-0.15 | 14.5-17.5 | 15-18 | 4.0-7.0 | 2.5 | -- | -- | -- | -- | 1.0 | 1.0[c] | 0.35V, 3.0-5.25W | Combustion chambers, collector rings |
| | 57 | 0.10 | 16 | 17 | 5 | -- | -- | -- | -- | -- | 0.8 | 0.7 | 4W | |
| Hastelloy D | Bal | 0.12 | 1.0 | -- | 2.0 | 1.50 | 2.0-4.0 | -- | -- | -- | 0.5-1.25 | 8.5-10.0 | -- | Corrosion-resistant alloy |
| | 82 | 0.10 | -- | -- | 1.0 | 1.50 | 3.0 | -- | -- | -- | 1.0 | 9.0 | -- | |
| Hastelloy F | 44 | 0.05-0.12 | 21-23 | 5.5-7.5 | Bal | 2.5 | -- | -- | -- | 1.75-2.50 | 1.0-2.0 | 1.0[c] | 1.0W | -- |
| Hastelloy X | Bal | 0.05-0.15 | 20.5-23 | 8.0-10.0 | 17-20 | 0.5-2.5 | -- | -- | -- | -- | 1.0 | 1.0[c] | 0.2-1.0W | Jet-engine parts |
| | 45 | 0.10 | 22.0 | 9.0 | 20 | 1.5 | -- | -- | -- | -- | | | 0.6W | |
| Hastelloy N | 67-72 | 0.04-0.08 | 6.0-8.0 | 15-18 | 5.0 | -- | -- | -- | -- | -- | 0.8 | 0.5[c] | Al + Ti = 0.5 | Resistance to hot fluoride salts |

TABLE I. (Continued)

| Trademark | Compositions, weight per cent | | | | | | | | | | | | Uses |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | $Ni^{(a)}$ | C | Cr | Mo | Fe | Co | Cu | Al | Ti | $Cb^{(b)}$ | Mn | Si | Others | |
| | | | | | | | Alloys Capable of Precipitation Hardening | | | | | | | |
| Monel K-500 | 65.0 | 0.15 | -- | -- | 1.00 | -- | 29.5 | 2.80 | 0.50 | -- | 0.60 | 0.15 | -- | Pumps, shafts, impellers |
| Monel 501 | 65.0 | 0.23 | -- | -- | 1.00 | -- | 29.5 | 2.80 | 0.50 | -- | 0.60 | 0.15 | -- | Gyroscope parts and small machined products |
| Inconel 600 | 76.0 | 0.04 | 15.8 | -- | 7.20 | -- | 0.10 | -- | -- | -- | 0.20 | 0.20 | -- | Jet-engine, heat-exchanger, and nuclear-reactor components |
| Inconel 604 | 74.0 | 0.04 | 15.8 | -- | 7.20 | -- | 0.10 | -- | -- | 2.0 | 0.20 | 0.20 | -- | Woven wire belts for furnaces, steam-turbine nozzle partitions |
| Inconel 625 | 61.0 | 0.05 | 22.0 | 9.0 | 3.00 | -- | 0.10 | -- | -- | 4.0 | 0.15 | 0.30 | -- | New alloy being evaluated for service up to 1200 feet |
| Inconel 700 | 46.0 | 0.12 | 15.0 | 3.75 | 0.70 | 28.5 | 0.05 | 3.00 | 2.20 | -- | 0.10 | 0.30 | -- | Turbine blades and rotors |
| Inconel 702 | 79.5 | 0.04 | 15.6 | -- | 0.35 | -- | 0.10 | 3.40 | 0.70 | -- | 0.05 | 0.20 | -- | Afterburner liners |
| Inconel 718 | 52.5 | 0.04 | 19.0 | 3.0 | 18.0 | -- | 0.10 | 0.60 | 0.80 | 5.2 | 0.20 | 0.20 | -- | Hydrofoils, space craft, jet engines, rocket motors, supersonic aircraft, cryogenic applications |
| Inconel 721 | 71.0 | 0.04 | 16.0 | -- | 7.20 | -- | 0.10 | -- | 3.00 | -- | 2.25 | 0.12 | -- | Internal-combustion-engine valves |
| Inceonl 722 | 75.0 | 0.04 | 15.0 | -- | 6.50 | -- | 0.05 | 0.60 | 2.40 | -- | 0.55 | 0.20 | -- | Jet-engine components |
| Inconel X-750 | 73.0 | 0.04 | 15.0 | -- | 6.75 | -- | 0.05 | 0.80 | 2.50 | 0.85 | 0.70 | 0.30 | -- | Gas-turbine parts, springs, bolts, bellows, aircraft sheet, vacuum envelopes |
| Inconel 751 | 72.5 | 0.04 | 15.0 | -- | 6.75 | -- | 0.05 | 1.20 | 2.50 | 1.00 | 0.70 | 0.30 | -- | Jet-engine turbine blades, diesel exhaust valves |
| Permanickel 300 | 98.6 | 0.25 | -- | -- | 0.10 | -- | 0.02 | -- | 0.50 | -- | 0.10 | 0.06 | 0.35 Mg | Springs, grid side rods, and lateral windings |
| Duranickel 301 | 94.0 | 0.15 | -- | -- | 0.15 | -- | 0.05 | 4.50 | 0.50 | -- | 0.25 | 0.55 | -- | Springs, glass molds, plastic extrusion, press parts |
| Inconel 713C | 66-77 | 0.20 | 11-14 | 3.5-5.5 | 5.0 | -- | -- | 5.5-6.5 | 0.25-1.25 | 1.0-3.0 | 1.0 | 1.0 | 0.02B, Zr | Jet-engine blades, parts |
| | 72 | 0.12 | 13 | 4.5 | 1 | -- | -- | 6 | 0.6 | 2.25 | 0.15 | 0.4 | -- | |
| DCM | 63-70 | 0.08 | 14-16 | 4.5-6.0 | 4.0-6.0 | -- | -- | 4.4-4.8 | 3.35-3.65 | -- | 0.10 | 0.15 | 0.07-.09B | Gas-turbine blades, parts |
| | 68 | 0.05 | 14.3 | 5.3 | 4.6 | -- | -- | 4.4 | 3.4 | -- | | | 0.08B | |
| Hastelloy R-235 | Bal | 0.16 | 14-17 | 4.5-6.5 | 9.0-11.0 | 2.5 | -- | 1.75-2.25 | 2.25-2.75 | -- | $0.25^{(c)}$ | $0.6^{(c)}$ | $0.005B^{(c)}$ | Gas-turbine and jet-engine parts |
| | 63 | 0.15 | 15.5 | 5.5 | 10.0 | -- | -- | 2 | 2 | -- | | | -- | |
| Waspaloy | 56 | 0.05 | 19.0 | 4.3 | 1.0 | 14.0 | -- | 1.3 | 3.0 | -- | 0.70 | 0.40 | 0.005B<br>0.06Zr | Jet-engine blades, parts |
| Nimonic 80 | 70-77 | 0.1 | 18-21 | -- | 5.0 | 2.0 | -- | 0.5-1.8 | 1.8-2.7 | -- | 1.0 | 1.0 | -- | -- |
| | 76 | 0.05 | 20 | -- | 0.5 | | -- | 1.0 | 2.3 | -- | 0.7 | 0.5 | -- | |
| Nimonic 80A | 70-77 | 0.1 | 18-21 | -- | 5.0 | 2.0 | -- | 0.5-1.8 | 1.8-2.7 | -- | 1.0 | 1.0 | -- | -- |
| | 75 | 0.04 | 21 | -- | 0.5 | | -- | 0.6 | 2.5 | -- | 0.7 | 0.5 | -- | |
| Nimonic 90 | 50-62 | 0.1 | 18-21 | -- | 5.0 | 15-21 | -- | 0.8-2.0 | 1.8-3.0 | -- | 1.0 | $1.5^{(c)}$ | -- | -- |
| | 58 | 0.10 | 19.5 | -- | | 18.0 | -- | 1.2 | 2.4 | -- | | | -- | |
| Nimonic 95 | 50-62 | 0.15 | 18-21 | -- | 5.0 | 15-21 | 0.5 | 1.4-2.5 | 2.3-3.5 | -- | 1.0 | $1.0^{(c)}$ | -- | -- |
| | 50 | | 20.0 | -- | | 20.0 | -- | 2.0 | 3.0 | -- | | | -- | |
| Nimonic 100 | 50-62 | 0.30 | 10-12 | 4.5-5.5 | 2.0 | 18-22 | -- | 4.0-6.0 | 1.0-2.0 | -- | -- | $0.5^{(c)}$ | -- | -- |
| | | | 11.0 | 5.0 | | 20.0 | -- | 5.0 | 1.5 | -- | -- | | -- | |
| Udimet 500 | 46-55 | 0.15 | 15-20 | 3.0-5.0 | 4.0 | 13-20 | -- | 2.5-3.25 | 2.5-3.25 | -- | 0.75 | $0.75^{(c)}$ | 0.005B<br>0.06Zr | Gas-turbine parts, sheet, bolting |
| | 52 | 0.12 | 19.0 | 4.0 | 2.0 | 19.0 | -- | 3.0 | 3.0 | -- | 0.7 | | 0.005B<br>0.05Zr | |
| Udimet 700 | 46-55 | 0.15 | 13-17 | 4.5-5.75 | 1.0 | 17-20 | -- | 3.75-4.75 | 3.0-4.0 | -- | | | $0.10B^{(c)}$ | Jet-engine parts |
| | 53 | 0.12 | 15.0 | 5.1 | 0.75 | 18.5 | -- | 4.25 | 3.5 | -- | | | 0.08B | |

TABLE I. (Continued)

| Trademark | Ni[a] | C | Cr | Mo | Fe | Co | Cu | Al | Ti | Cb[b] | Mn | Si | Others | Uses |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Compositions, weight per cent | | | | | | | | | | | | | |
| **Alloys Capable of Precipitation Hardening (Continued)** | | | | | | | | | | | | | | |
| Unitemp 1753 | 51 | 0.25 | 16.5 | 1.5 | 9.5 | 7.5 | -- | 2.0 | 3.1 | -- | | | 0.008B, 8.5W, 0.05Zr | Gas-turbine components, buckets, wheel fasteners, rings, spacers |
| | Bal | 0.02-0.28 | 15.5-17.5 | 1.0-2.0 | 7-11 | 6.5-8.5 | -- | 1.75-2.25 | 2.9-3.4 | | | | 0.002-0.010B, 0.02-0.10Zr, 7.5-9.5W | |
| M-252 | 51-57<br>55 | 0.10-0.20<br>0.15 | 18-20<br>19.0 | 9.0-11.0<br>10.0 | 5.0<br>2.0 | 9.0-11.0<br>10.0 | --<br>-- | 0.5-1.25<br>1.0 | 2.25-2.75<br>2.5 | --<br>-- | 0.5-1.5<br>1.0 | 0.3-1.0<br>0.7 | 0.005B<br>0.06Zr | -- |
| Rene 41 | 52-58<br>55 | 0.06-0.12<br>0.10 | 18-20<br>19.0 | 9-10.5<br>10.0 | 5.0<br>1.0 | 10-12<br>10.0 | --<br>-- | 1.5-1.8<br>1.5 | 3.0-3.3<br>3.0 | --<br>-- | 0.5<br>0.05 | 0.5[c]<br>0.1 | 0.01B<br>0.005B | Jet-engine components, sheet bolting, turbine disks |
| Nicrotung | 61 | 0.10 | 12.0 | -- | | 10.0 | -- | 4.0 | 4.0 | -- | | | 0.05B, 8.0W, 0.05Zr | High-strength parts |
| **Dispersion-Hardening Alloys** | | | | | | | | | | | | | | |
| TD nickel | Bal | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | 2.0 $ThO_2$ | Turbine blades |

Note: When two compositions are given, maximum compositions or ranges are in the first line; those in the second line are typical compositions.

(a) Includes small amount of cobalt unless otherwise specified.

(b) Includes tantalum.

(c) Indicates minimum amount.

(d) Indicates maximum amount.

TABLE II. EFFECT OF ELEMENTS ON JOINING NICKEL AND HIGH-NICKEL ALLOYS (REFS. 6-8)

| Beneficial | No Real Effect[a] | Variable | Harmful |
|---|---|---|---|
| Columbium | Manganese | Aluminum | Sulfur |
| Magnesium | Copper | Titanium | Phosphorus |
| | Chromium | Carbon | Lead |
| | Iron | Molybdenum | Zirconium |
| | Cobalt | Silicon | Boron |
| | | | Oxygen |
| | | | Nitrogen |
| | | | Hydrogen |

(a) Within normal concentration ranges.

Sulfur - Sulfur causes hot shortness. It is probably the most harmful element encountered when joining nickel-base alloys. Sulfur has a very limited solubility in nickel and forms low-melting sulfide materials that embrittle the alloy by collecting at grain boundaries. Vacuum melting of the alloys or magnesium fixation are means of overcoming the bad effects of sulfur. High-quality, nickel-base materials may be ruined by poor removal of sulfur-containing machining compounds, crayon marks, or shop dirt before joining.

Magnesium - Magnesium sulfides have melting points much higher than nickel sulfides. Thus, sulfur fixation is accomplished with magnesium. Unfortunately, the recovery of magnesium is poor, especially when fusion welding with covered electrodes.

Columbium - Columbium is used to prevent the occurrence of hot cracking in nickel-iron-chromium alloys containing silicon. The amount of columbium required varies with the nickel/iron ratio. The higher the ratio the more columbium required.

Lead - Lead causes hot shortness in nickel-alloy weld metal. It is seldom found in high-quality base or filler metals.

Phosphorus - Phosphorus, like lead, is seldom found in nickel-base alloys. Phosphorus in very low concentrations can cause hot cracking. Generally, its detrimental effects are similar to those of lead and sulfur.

Boron - Boron cannot be considered completely detrimental to nickel-base alloys because it has been added to improve the high-temperature mechanical properties. However, the presence of boron in even very low concentrations causes cracking of weld metal, heat-affected zones, and heated parent metals.

Zirconium - Zirconium, like boron, can be added to improve the high-temperature mechanical properties. Such additions ruin weldability. A few tenths of 1 per cent zirconium makes nickel-base alloys very weld-crack sensitive. Zirconium-nickel alloys are not fusion weldable.

Carbon - Carbon in the nonchromium-bearing nickel alloys may cause trouble if the service temperature is in the range 600 to 1400 F because the thermal cycles involved in joining promote carbon precipitation as intergranular graphite. This weakens the microstructure. The remedy is to limit the carbon content to below 0.02 per cent. In the chromium-bearing nickel-base alloys carbon in normal amounts causes no problems.

Molybdenum - Molybdenum in the amount of 20 to 30 per cent in two-phase alloys causes hot cracking. Single-phase alloys do not crack seriously. Thus, molybdenum should be a problem with only one or two of the important alloys.

Silicon - Silicon causes hot cracking in nickel-base alloys. The severity of this effect is quite variable, depending both upon the alloy and the joining process used. It is especially bad in high-nickel chromium-bearing alloys. Columbium is often added to high-nickel alloys to counteract the effects of silicon.

| | |
|---|---|
| Aluminum | - Aluminum is added to nickel alloys as a deoxidizer and to develop age-hardening properties. In general, aluminum has the same effect on joining as silicon. The usefulness of aluminum as an age hardener in high-temperature high-nickel alloys makes it a desirable addition to fusion welding filler metals for these alloys. Usually, however, hot-cracking problems arise before the full benefit of the aluminum is obtained. Thus, other means must be found to match weld-metal properties with base-metal properties. |
| Titanium | - Titanium is added to high-nickel alloys for two reasons: (1) to develop age-hardening response and (2) to reduce gas porosity. The effect of titanium when welding these alloys is very much like that of aluminum. The weld metal becomes hot-short and crack-free welds become hard to obtain, especially in restrained joints. |
| Oxygen, nitrogen, and hydrogen | - Oxygen, nitrogen, and hydrogen are important from the standpoint of weld-metal porosity. These elements have not been shown to promote cracking in nickel and nickel-base alloys. |

Some alloying elements have a considerable effect in joining operations other than fusion welding, such as brazing. Other alloying elements have only a small effect. The most important consideration in brazing after the proper choice of brazing filler metal is what surface contaminants are produced by the alloying elements in the base material. Nickel-base alloys containing aluminum and/or titanium require special consideration for successful brazing. This will be discussed later in this report.

## JOINT DESIGN

Design of joints to be welded is important for all joining processes. Selection of the welding process can be limited by the type of joint. Conversely, some welding processes are more or less tolerant than others of joint design variations. Joints with square abutting edges are suitable for arc or electron-beam fusion welding for thin gages of nickel and nickel-base-alloy sheet. Thicker sheet requires a more complex joint design. Typically, such preparation involves machining bevels or contours on the abutting edges. Part

tolerances also are an important consideration in establishing good joint designs. Close tolerances are always preferred, but they cannot always be produced in production parts.

Joints designed for TIG, MIG, or electron-beam welding nickel and nickel-base alloys normally are prepared by machining so as to provide a good joint fitup. The joints are machined by milling, shaping, grinding, and other conventional machining methods.

Suggested joint designs for arc welding of nickel-base alloys are shown in Figure 1 (Ref. 9). Joint preparations for similar thicknesses of steel are also shown for comparison. Nickel and high-nickel alloys do not flow as readily as mild steel, and weld penetration normally is lower. Consequently, greater operator skill is required to prepare satisfactory welds. Joint designs should require normal heat input rates for welding because high heat input rates can result in loss of residual deoxidizing agents. Since electron-beam fusion welds are very narrow, square-butt joints are employed to provide a good fitup over the full thickness of the joint.

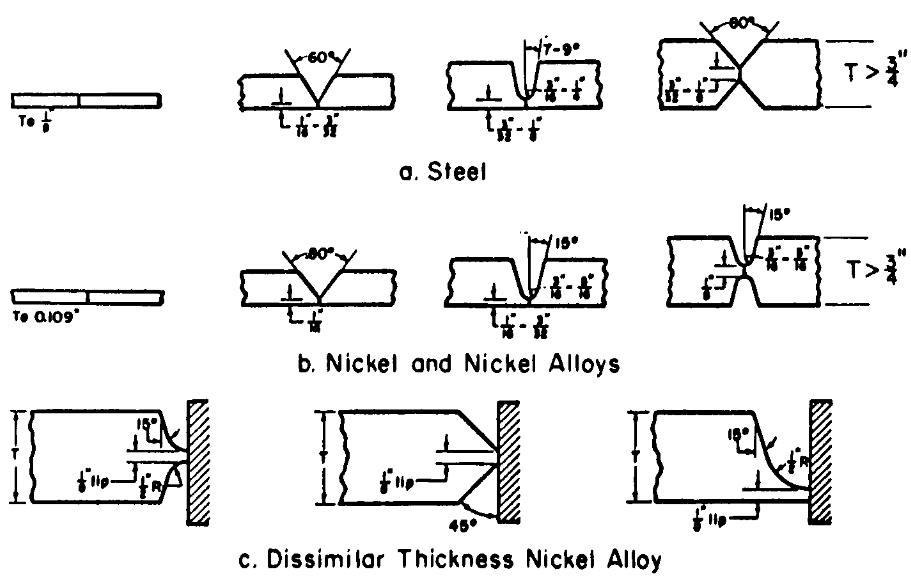



FIGURE 1. JOINT PREPARATIONS FOR ARC WELDING NICKEL AND NICKEL-BASE ALLOYS AND COMPARABLE JOINTS IN STEEL (REF. 9)

Resistance-spot, seam, and projection welding usually involve joints that consist of overlapping layers of material. Multiple layers may be included in a single joint. Many of the joint designs

used for resistance welding are not intended to transmit transverse tensile loads. In resistance welding such factors as edge distances, flatness, interspot spacings, initial sheet separation, and accessibility are important in the selection of a suitable joint design.

Joints designed for brazing also require controlled fitup. There are many variations of braze-joint designs but it is useful to consider that joint clearance must be controlled at brazing temperatures. The effect of joint clearance on strength of brazed joints is illustrated in Figure 2 (Ref. 10). The shape of the joint clearance-strength curve and optimum strength is determined by the composition of the base and filler metals, brazing parameters, and method of testing.

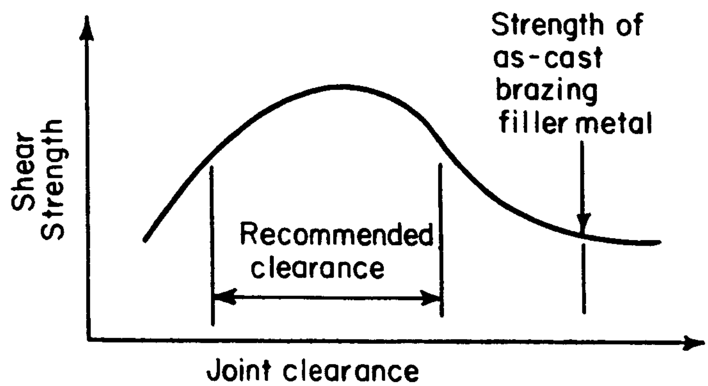



FIGURE 2. EFFECT OF JOINT CLEARANCE ON THE SHEAR STRENGTH OF BRAZED JOINTS (REF. 10)

## CLEANING

Cleaning is very important to the successful welding of nickel and nickel-base alloys. The degree of cleanliness before, during, and often after welding can affect weld quality. Clean materials are particularly vital when joining electronic components (Ref. 11). Two main types of surface contamination must be considered when cleaning:

(1) Surface dirt such as paint, grease, and oil
(2) Oxide films and scales.

Proper surface preparation is necessary to

(1) Prevent the harmful effects of sulfur, lead, and other elements that are often present in paint, oil, and other surface dirt

(2) Prevent the entrapment of oxide film or scale.

Surface Dirt, Grease, and Oil. Both the weld metal and adjacent base-metal areas can become contaminated by surface dirt. It is evident that any foreign material on the joint surfaces can be trapped easily in the weld and cause contamination. Foreign material on surfaces outside the joint also can contaminate the parts during joining operations. When the parts are heated, elements such as sulfur and lead can diffuse into the parent parts. This is often referred to as "burning in". Burning in of elements in crayon, pencil, or paint markings can result in severe cracking.

Processes for removing foreign matter from the surfaces of nickel and nickel-base alloys are the same as for cleaning other metal products (Ref. 12). Grease and oil are removed with commercial solvents and by vapor degreasing. Soaps can be removed with hot water. Removal of soluble oils, tallow, fats, and fatty acid combinations requires a more complex cleaning procedure. The following is a typical cleaning procedure:

(1) Immerse in a hot solution of 10 to 20 per cent sodium carbonate or sodium hydroxide, 10 to 20 per cent trisodium phosphate, and water, for 10 to 30 minutes

(2) Rinse thoroughly with water.

This alkaline treatment also is suggested to remove films that remain after solvent cleaning. Drying should be performed with clean, dry air to avoid contaminating the surfaces again with oil or other foreign material from the air supply.

The work should be protected from contamination during the joining operation. Furnace refractories, work supports, and unclean tooling can cause contamination.

Tarnish and Scale. Three types of surface conditions are formed on nickel and nickel-base alloys.

(1) Tarnish
(2) Reduced oxides
(3) Oxide film or scale.

The procedures used for removing these conditions are determined by alloy composition and by thermal history.

Tarnish is formed on nickel when annealing is performed in a strongly reducing atmosphere, and cooling is performed in the absence of oxygen or by quenching in a 2 per cent by volume alcohol solution. When nickel alloys are hot worked, oxide films form on the surface. When heat treated in a reducing atmosphere and cooled in the absence of oxygen, the oxide is reduced to metallic nickel (and metallic copper when the alloy contains copper). Neither tarnish nor reduced oxide films interfere with joining. When desired, both can be removed by acid pickling.

Alloys containing chromium and iron form oxide films even when heated and cooled in atmospheres that keep other alloys bright. When heated in air, all nickel alloys can oxidize. These oxide films have much higher melting temperatures than the parent metal and, if not removed, cause difficulties in joining. In arc welding, the oxide remains as a crust cover on the underlying metal; this makes it difficult for the welding operator to maintain proper control of the weld pool. Also, the oxides can be trapped in the weld metal. In addition, the oxides can interfere with all types of resistance welding, brazing, soldering, and solid-state bonding operations.

Light oxides are removed from nickel and nickel-base alloys by acid pickling. When properly heat treated, nickel alloys usually can be pickled in the following solution (Ref. 12):

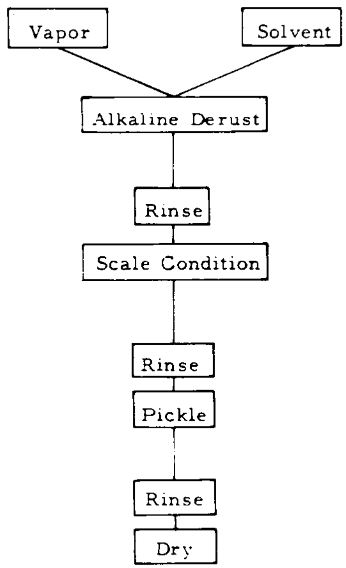
| | |
|---|---|
| Nitric acid - 42° Bé | - 296 cc |
| Hydrofluoric acid - 30- Bé | - 50 cc |
| Water | - 1000 cc |

Usual pickling conditions are:

| | |
|---|---|
| Temperature | - 125 F (max) |
| Time | - 5 to 60 minutes. |

Pickling procedures used by one fabricator are shown in Figure 3 for several selected nickel-base alloys (Ref. 13). Some undesirable effects can be produced during pickling operations. These are:

(1) Copper may deposit on the parts. Prevention of coppering is accomplished by maintaining the copper ions in cupric rather than cuprous form.




Degrease

Immerse in alkaline derust solution for 20 minutes

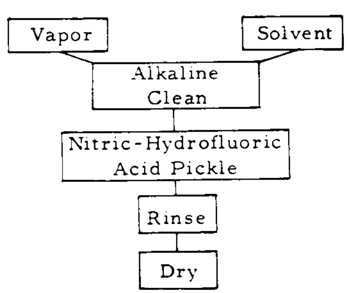
Immerse in sodium hydroxide-sodium dichromate solution for 20 minutes

Pickle in nitric-hydrofluoric acid solution for 30 minutes

Rinse thoroughly

Blow dry with compressed air

a. Inconel X




Degrease

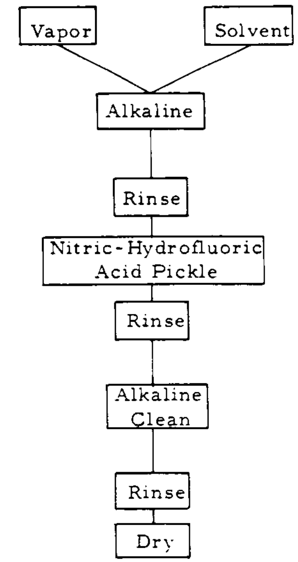
Pickle in nitric-hydrofluoric acid solution

Rinse in tap water

Dry

b. Nonaged Inconel X and Hastelloy Alloys X and R235

1. Cleaning Before Brazing or Welding




Solvent and/or vapor degrease

Immerse in alkaline cleaning solution (using no current) for 5 to 15 minutes

Rinse in cold water

Pickle in nitric-hydrofluoric acid solution for 1 to 3 minutes

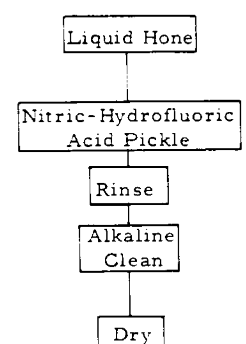
Rinse in cold water

Neutralize in alkaline cleaning solution for 1 to 5 minutes (using no current)

Rinse in hot water

Air or oven

2. Scale Removal After Heat Treatment




Liquid hone

Pickle in nitric-hydrofluoric acid solution for 30 to 60 seconds

Rinse in cold water

Neutralize in alkaline cleaning solution for 1 to 5 minutes (using no current)

Air or oven

c. Nonaged Inconel 718

(2) Nitric-hydrofluoric acid baths must be used with care to prevent intergranular attack. Time in the bath should be kept at a minimum, and the temperature should never exceed 125 F.

When planning pickling procedures, producers of the alloys and producers of proprietary pickling materials should be contacted for additional information.

Heavier oxides can be removed by fused salt pickling. Removal of heavy scale also can be done by abrasive blasting or grinding followed by a flash pickle. Aluminum-oxide blasting followed by manual stainless-steel wire brushing has been used for interpass cleaning when welding Inconel X (Ref. 14).

After cleaning, the parts may be exposed to the open atmosphere where dust and fine dirt particles may settle out on the joint surfaces and adjacent areas. The "fallout" dirt also can contaminate joints in nickel and nickel-base alloys. This kind of dirt may be removed by carefully wiping the joint area with lint-free cloths dampened with a solvent such as methyl ethyl ketone. So-called "white glove" operations are often used to prevent contamination after careful cleaning. Cleaned material should be joined within a few hours or protected with lint-free and oil-free wrapping for storage until needed. Some recleaning of material that has been in storage may be required before certain joining operations.

The effectiveness of cleaning methods is evaluated by various methods. The most unpopular method is discovering porosity, cracks, or other evidence of contamination in a completed weldment. A common method for evaluating the cleanliness of a part emerging from descaling and pickling operations is to observe water breaks during the water rinse. No water break indicates a clean surface while the presence of a water break indicates some foreign material remaining on the surface. Contact-resistance measurements can be made to compare the effectiveness of cleaning methods prior to joining.

Fabricated parts that are to be hot formed or stress relieved must be clean. In view of the problems in cleaning complex parts, it may be simpler to keep such parts from becoming dirty during joining operations. This will require careful handling and storage throughout all operations associated with the actual joining.

The coatings of shielded metal-arc-welding electrodes help control oxidation of the weld zone by forming a slag over the surface of the weld and by releasing large quantities of gas that exclude air from the weld area. When multipass welding procedures are used, all slag should be removed before starting subsequent passes. After welding, all slag must be removed from the weldment. Slag removal is especially important when weldments must operate at elevated temperatures. If slag is left on the weldment and becomes molten during service, severe attack of the metal can occur. Fluxes used for submerged-arc welding (Refs. 15, 16), brazing, and soldering also should be removed carefully after joining is completed to prevent attack or corrosion in later service.

Handling and Storage After Cleaning. Joining should be performed as soon as possible after cleaning. Oxides begin to form immediately after exposure to open-air atmospheres. Although the oxides may be extremely thin and invisible, they can interfere with joint quality and consistency of quality in operations like resistance welding and solid-state diffusion welding. Care must be exercised to prevent paint or crayon markings, shop dirt, condensed moisture, and other harmful foreign matter from interfering with joint quality.

## MATERIAL CONDITION

Nickel and nickel-base alloys base metals can be joined in the annealed, the cold-worked, or the heat-treated condition. Pure nickel and the solid-solution-hardening alloys usually are joined in the annealed condition. Some precipitation-hardening alloys are joined only after they are heat treated to the solution-treated condition.

## TOOLING

The tooling used for joining nickel and nickel-base alloys generally is no different than tooling used for joining other materials. Welding equipment usually is purchased from commercial welding-equipment suppliers, but tooling such as fixtures to hold the parts during welding, backup bars, and shielding devices is often designed and fabricated for a particular application. Equipment for joining is described adequately in the welding literature and in manufacturers' literature and, therefore, is omitted from this discussion. Important considerations for tooling and inert-gas-shielding arrangements, however, are described in the following sections.

Fixtures and Fixture Materials. Proper tooling helps to provide consistently good-quality welds by minimizing distortion and maintaining alignment. Fixturing devices may range from simple clamps to hold parts in position to more elaborate holding devices designed for specific parts. Simple fixtures are adequate for joining when other means are used to insure adequate shielding, for example, when electron-beam or arc welding in an enclosed chamber. However, for fusion-welding operations conducted outside of chambers, fixtures can provide a much more effective safeguard against weld contamination than other shielding devices. Tooling often is used to cool the weld area rapidly so that exposure in the temperature range of high chemical reactivity is minimized. Such tooling is referred to as "chill" type. When improperly designed, tooling can cause problems. Tooling may restrain the weld zones so greatly that cracking may result. Weak tooling can be pulled out of shape during welding and allow the weldment, in turn, to distort.

Tooling in actual contact with nickel and nickel-base alloys on both root and face sides of welds usually is made from copper, but other materials can and have been used (Ref. 17). Often, these materials are used in the form of bar-type inserts or sheet- or plate-type facing plates for fixtures. Access-side hold-down bars and backup bars extend the full length of the weld and often contain inert-gas passages for weld face and root shielding. When grooved backup bars are used, the grooves should be shallow to minimize burnthrough and to control the root reinforcement contour. In addition, the grooves should be round to prevent entrapment of slag in corners. Considerable trouble with welding operations is inevitable unless weld-joint preparations are accurately machined, and the joints are held properly in the welding fixtures.

The tooling used in resistance welding nickel alloys is generally similar to tooling used in resistance welding other materials. Resistance-welding tooling consists of suitable fixtures or jigs to hold the parts in proper position for welding and to conduct welding current to the parts. Sometimes tooling is also designed to index the part through the welding equipment to insure that welds are made at the proper positions. The same general rules followed in designing any resistance-welding tooling should be followed for tooling designed for use with nickel and nickel-base alloys. Generally, this means that nonmetallic or nonmagnetic components should be used exclusively, and the tooling should not contaminate the nickel-base alloys.

Tooling for soldering and brazing also needs to be considered carefully. Tooling for use with these processes must hold the parts in position during joining, and it should not contaminate the filler metals or the base metals.

Tooling for Inert-Gas Shielding. Protection of nickel from contamination during joining operations can be accomplished in several ways:

(1) Perform the operation inside an inert-gas-filled chamber

(2) Perform the operation with flowing inert gases through the welding torch, backups, fixtures, and auxiliary tooling

(3) Perform the operation in a good vacuum in a closed chamber

(4) Perform the operation using suitable fluxes.

A wide variety of tooling has been designed to provide needed shielding during joining operations. Although shielding devices vary in detail, they all serve the same basic purpose, i. e., protecting the metal being joined from gases that can contaminate the hot metal.

Several types of shielding and controlled-atmosphere chambers are in use for welding and brazing. Such chambers are designed to contain the entire component to be joined, or in some cases, merely a weld-joint area. The air in the chamber is replaced with inert gas by (1) evacuation and backfilling, (2) flow purging, or (3) collapsing the chamber and refilling it with inert gas. Welding chambers are particularly useful in the welding of complex components that would be difficult to fixture and protect properly in the air. Use of a welding chamber, however, is not a cure-all. The inert gas in many welding chambers can be of much poorer quality than the inert gas contained in the conventional flowing shields. Leakage of air or water vapor into a chamber atmosphere must be avoided to prevent contamination. Continuous monitoring devices that disclose contamination of a chamber atmosphere are available.

A tank-type controlled-atmosphere welding chamber for manual and machine gas tungsten-arc and gas metal-arc welding is shown in Figure 4 (Ref. 18). Many small chambers are made from plastic

domes and steel or stainless steel; stainless steel is preferred because it does not rust and is easier to clean. Several small-size chambers for welding small subassemblies are shown in Figure 5 (Refs. 19, 20). The adaptation of a small-size chamber to welding an oversize part is shown in Figure 6. (Ref. 20); only the localized area that is heated needs to be inert-gas shielded. A flexible plastic chamber is illustrated in Figure 7 (Ref. 21).

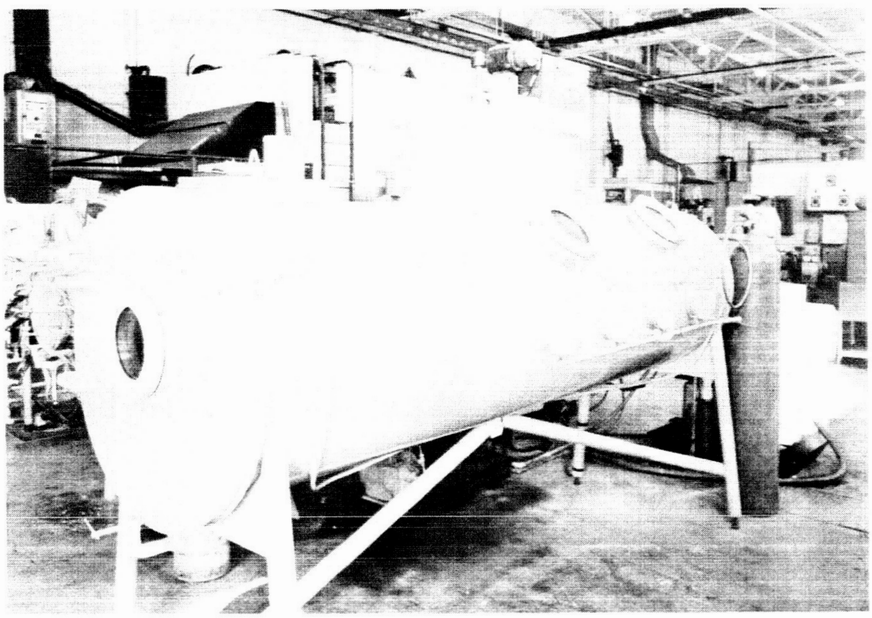
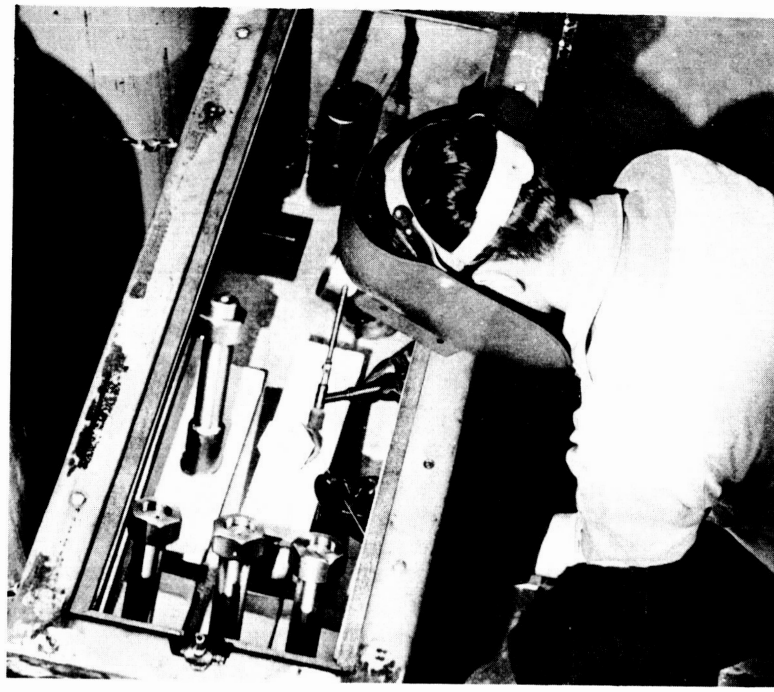


FIGURE 4. TANK-TYPE CONTROLLED-ATMOSPHERE WELDING CHAMBER (REF. 18)

Shielding gas used in these chambers may or may not flow through the torch, depending on the fabricator. Also, the shielding gas can be recirculated through a purifying train to remove undesirable gases that are evolved from the alloy being welded or from the chamber walls and tooling as these become heated.

For in-air welding with the gas tungsten-arc and gas metal-arc processes, shielding is provided in several ways:

(1) Flowing inert-gas shield through the torch to shield the molten weld pool and adjacent surfaces



a.

b.

FIGURE 5. SMALL-SIZE WELDING CHAMBERS (REFS. 19, 20)

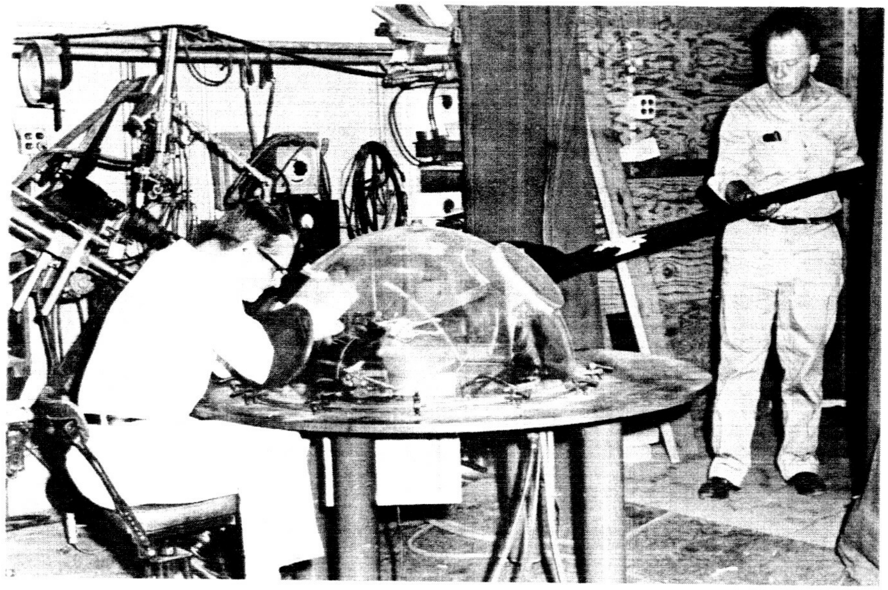


FIGURE 6. ADAPTATION OF A SMALL CHAMBER TO PROVIDE LOCALIZED SHIELDING OF A LARGE PART DURING WELDING (REF. 20)

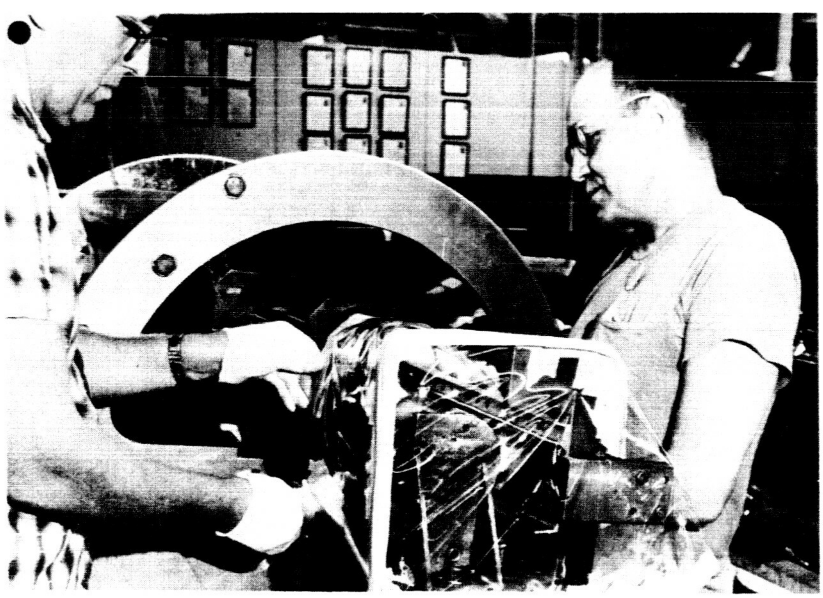


FIGURE 7. FLEXIBLE INERT-GAS-SHIELDING CHAMBER (REF. 21)

(2) Flowing inert-gas shield through a trailing shield to protect the weldment as it cools

(3) Flowing inert-gas shield through hold-down and backup bars. Shielding gases flowing through the hold-down bars provide additional shielding for the face side of the weld. The backup gas flow protects the root side of the weld during welding and during cooling of the weld metal.

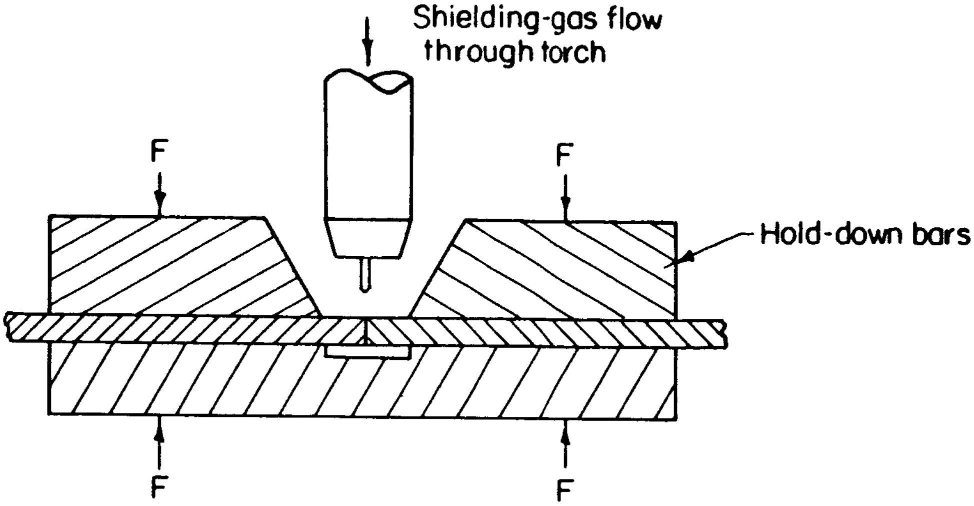
A variety of inert-gas-shielding devices have been developed for use when welding in open-air atmospheres. All are designed primarily for blanketing the hot metal from the surrounding air atmosphere. Figure 8 illustrates two different shielding methods that are used for metals like nickel, aluminum, and stainless steels. The hold-down and backup shielding method shown in Figure 8a is used in many joining operations. The shielding method shown in Figure 8b is used when better shielding is required. A torch-trailing-shield arrangement for gas tungsten-arc and gas metal-arc welding is shown in Figure 9 (Refs. 22, 23). The detachable-trailing-shield concept provides for interchangeable trailing-shield units for use with other joint designs or degrees of accessibility. Baffles also are used to help retain inert gases in desired areas and help prevent stray drafts from disturbing and deflecting the shield-gas-flow pattern (Refs. 19, 24). Similar concepts are used to protect the nonaccess (root) side of a weld joint (Refs. 19, 22-24). Figure 10 illustrates two shielding devices that were used to prevent root contamination in welding of pipe.

Advantage also is taken of the fact that argon tends to settle and displace air. Conversely, helium is best suited for displacing air when a rising gas flow is desirable. For in-air welding, trailing shields designed for MIG welding are usually considerably longer than those used in TIG welding. This is to insure good protection for the larger volumes of material that are heated during MIG welding, and which cool more slowly as a consequence.

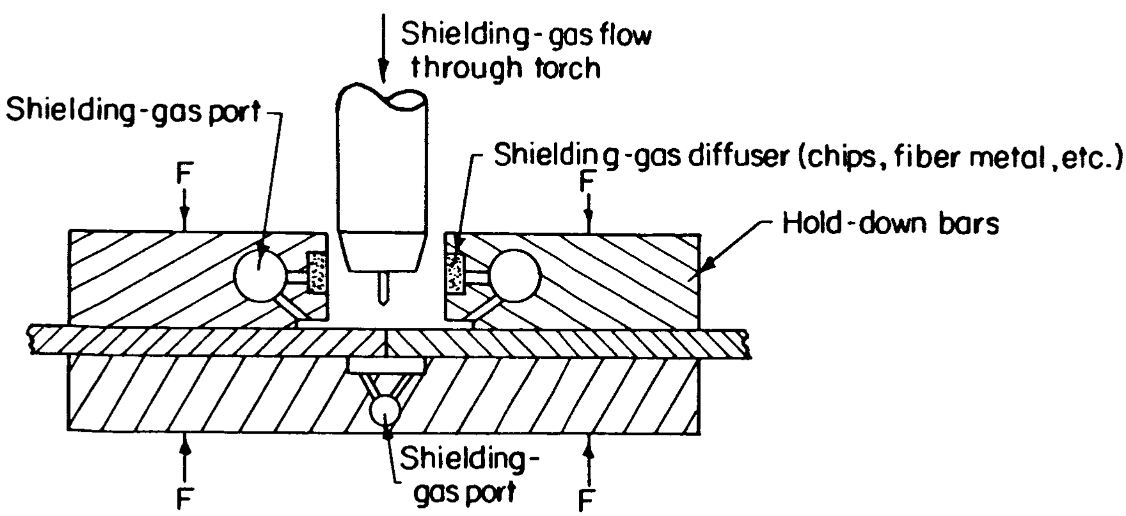
Inert-gas-shielding considerations also are important in designing joints for welding. Some joint designs cannot be protected adequately by inert gases except at great expense.

## RESIDUAL STRESS

Residual stresses are developed during all joining processes. The effects of residual stresses should be considered before joining




a. Weld Tooling for Aluminum and Stainless Steels




b. Special Tooling for Titanium (F represents clamping force)

FIGURE 8. ILLUSTRATION OF TOOLING FOR CONVENTIONAL AND SPECIAL GAS SHIELDING

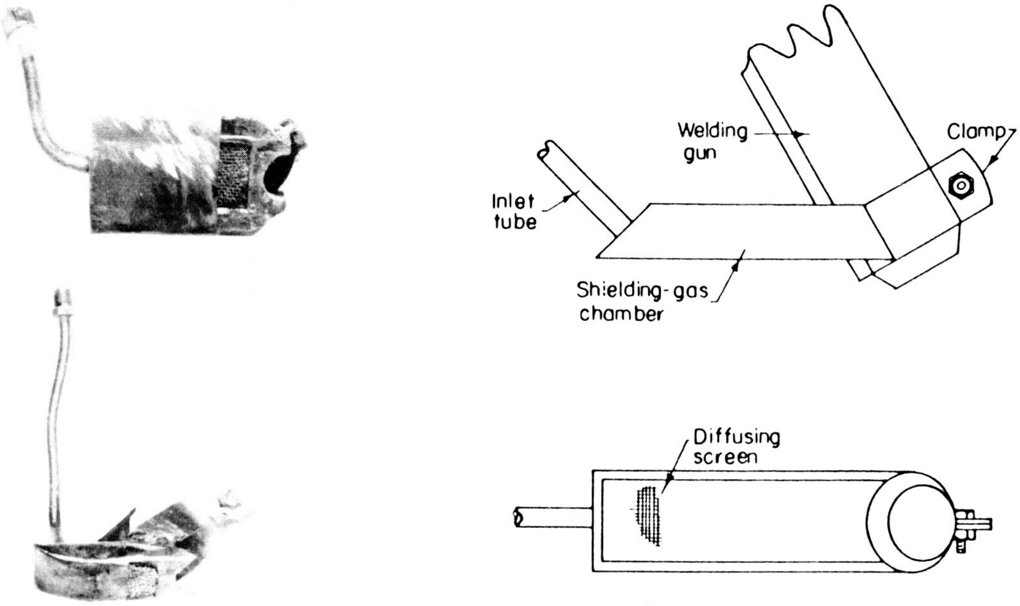



FIGURE 9. TRAILING SHIELDS (REFS. 22, 23)

Top left shows a wide shield for wide joint opening and capping passes; bottom left shows a narrow shield for root passes and narrow joint openings. Sketches at right show trailing-shield attachment to welding torch.

FIGURE 10. INTERNAL SHIELDING DEVICES FOR PROTECTING THE ROOT SIDES OF PIPE WELDS (REF. 19)

operations are started. Residual stresses are those that exist in a body without any external force acting. The residual stresses in a welded joint are caused by the contraction of the weld metal and the plastic deformation produced in the base metal near the weld during welding. Residual stresses in a welded joint are classified as follows: (1) "residual welding stress", which occurs in a joint free from any external constraint and (2) "reaction stress" or "locked-in stress", which is induced by an external constraint.

For most nickel-base alloys, a treatment between 900 and 2175 F for a period of time ranging from 5 minutes to several hours is recommended for stress relieving, depending on the particular alloy. Possible interactions between a thermal stress-relieving treatment and other changes in a material that may affect its properties must be anticipated. For example, age hardening will occur in Inconel X over a certain temperature range. A similar effect is found with other nickel-base alloys. Inconel X should be heated to the normal stress-relieving temperature range as rapidly as possible. Other methods of relieving the residual stresses in the alloy may be suitable. For example, mechanical treatments such as peening have been used to alter the residual-stress patterns and magnitude (Ref. 25).

Residual stresses in resistance welds can be altered and to some extent eliminated by either mechanical- or thermal-stress-relieving treatments. The application of mechanical-stress-relieving methods to spot welds is difficult because of the complexity of the residual-stress patterns and the limitations generally imposed by joint configurations. At best, mechanical techniques can probably only result in a redistribution of the residual-stress pattern and not the complete elimination of residual stress. On the other hand, thermal stress relieving can be used effectively to eliminate all residual stresses resulting from resistance welding. The most fruitful method of controlling residual stresses in resistance-welded joints may be by the selection of suitable process parameters.

Residual stresses generally are not a serious problem in brazed or solid-state-welded joints because heating and cooling of the parts are more uniform.

<u>Shrinkage and Distortion</u>. Joining processes are often characterized by thermal cycles that cause localized shrinkage. In turn, this shrinkage often causes distortion of the parts being joined. Figure 11 illustrates the changes in shape that occur just as the

result of welding a simple butt joint. More complex weldments obviously involve much more complex shrinkage and distortion patterns. Weld shrinkage must be planned for, since there is no absolute way to avoid it. Expected shrinkage values for typical weld configurations often are obtained before making production-welding applications. Also, a logical sequence of welding components involving several welds must be established with shrinkage in mind.

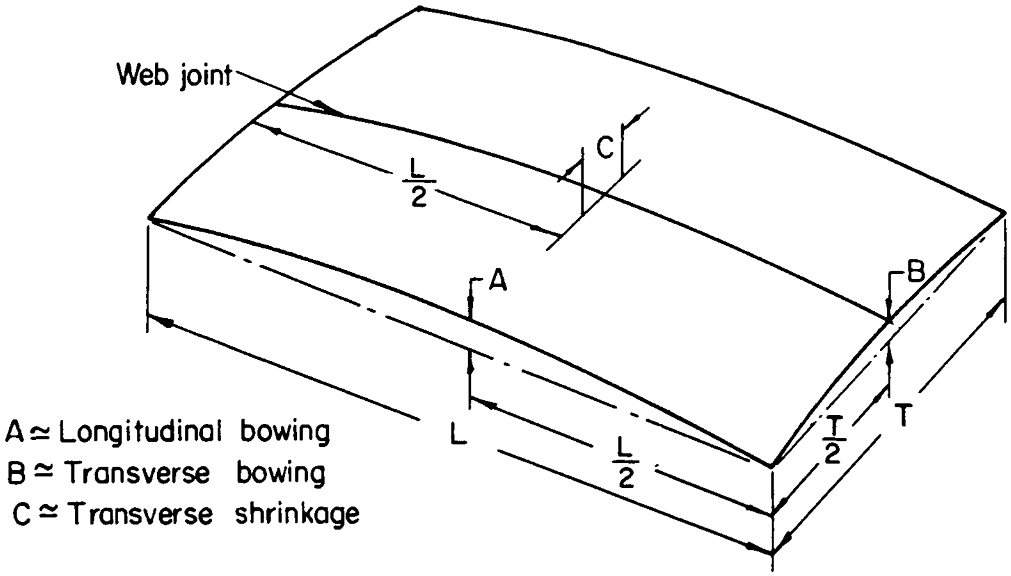



FIGURE 11. WELDMENT DISTORTION DUE TO FUSION WELDING

With the proper welding sequence, shrinkage can be turned into good use to minimize distortion. This is accomplished by properly balancing the various shrinkage forces developed. Shrinkage also can be controlled to some extent by the restraint imposed by tooling. Use of this technique is sometimes helpful in preventing serious part distortion. Freedom from distortion, however, does not mean that a weldment is not highly stressed. Quite often the converse is true. Shrinkage and distortion also are minimized by using low- and/or uniform-heat inputs. Unnecessary weld reinforcement also is undesirable from the standpoint of keeping shrinkage and distortion as low as possible.

Thermal cycles employed in resistance welding also result in highly localized shrinkage. This shrinkage may cause some distortion of the part being joined, but generally distortion is not as

noticeable in resistance-welded components as it is in fusion-welded parts.

The effects of weld shrinkage and subsequent distortion are generally minimized in resistance welding by starting the welding near the center of any component and following a welding sequence that involves moving progressively toward the edges of the component. Sequences of this type are not readily used during seam welding or roll spot welding, and consequently distortion may be more of a problem when these processes are used. Selection of improper welding sequences can also introduce various problems with sheet separation prior to welding. For example, if three welds are being made in a row and the two outside rows are welded first, then there is a good chance that the center row will be welded under conditions where excessive sheet separation is likely. In a case such as this, the center row should be welded first, followed by the outside rows.

Shrinkage and distortion are much less troublesome in brazing and solid-state welding, because usually heating is uniform.

Stress Distribution. The distribution of residual stresses is determined largely by joint geometry. Therefore, similar stress distributions are found in joints of similar geometry, regardless of how the joint was made. For example, resistance seam welding and TIG welding will result in a similar stress distribution in a long straight joint.

A typical distribution of residual stresses in a butt weld is shown in Figure 12a. The stress components concerned are those parallel to the weld direction, designated $\sigma_x$ and those transverse to the weld, designated $\sigma_y$. The distribution of the $\sigma_x$ residual stress along a line transverse to the weld, YY, is shown in Figure 12b. Tensile stresses of high magnitude are produced in the region of the weld; these taper off rapidly and become compressive after a distance of several times the width of the weld, then gradually approach zero as the distance from the weld increases. When contraction of the joint is restrained by an external constraint, the distribution of $\sigma_y$ is as shown by the broken line in Figure 12c. Tensile stresses approximately uniform along the weld are added as the reaction stress. An external constraint, however, has little influence on the distribution $\sigma_x$ residual stresses.

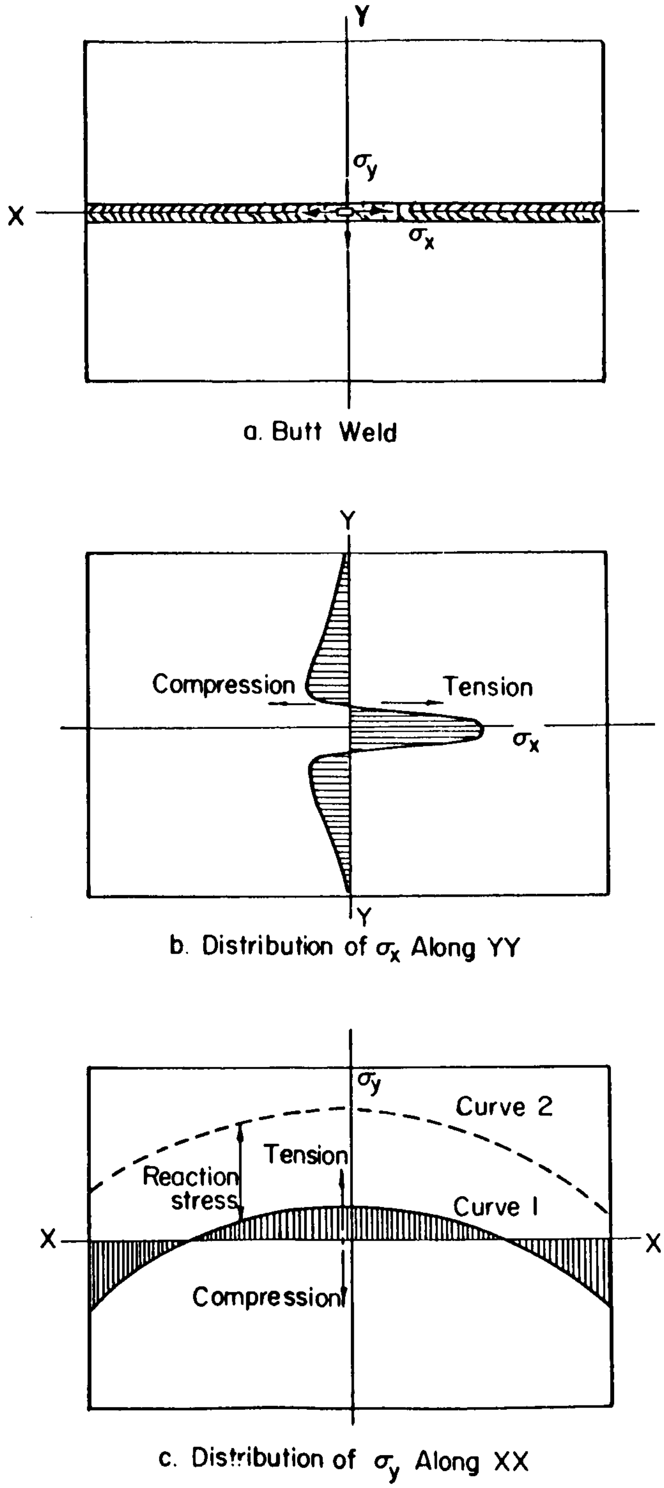



FIGURE 12. SCHEMATIC DISTRIBUTION OF RESIDUAL STRESSES IN A BUTT WELD

The maximum residual stress in the weld is determined by

(1) Expansion and contraction characteristics of the base metal and the weld metal during the welding thermal cycle

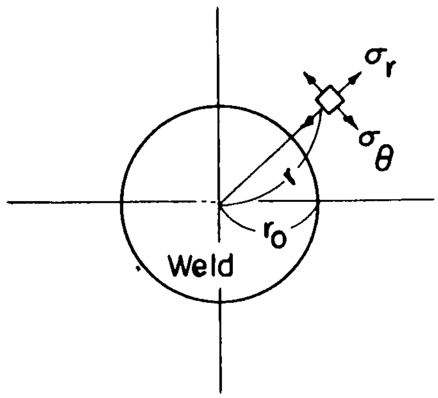
(2) Temperature versus yield-strength relationships of the base metal and the weld metal.

Much research in mild-steel weldments has shown that the maximum residual stress is limited to the yield strength of the weld metal.

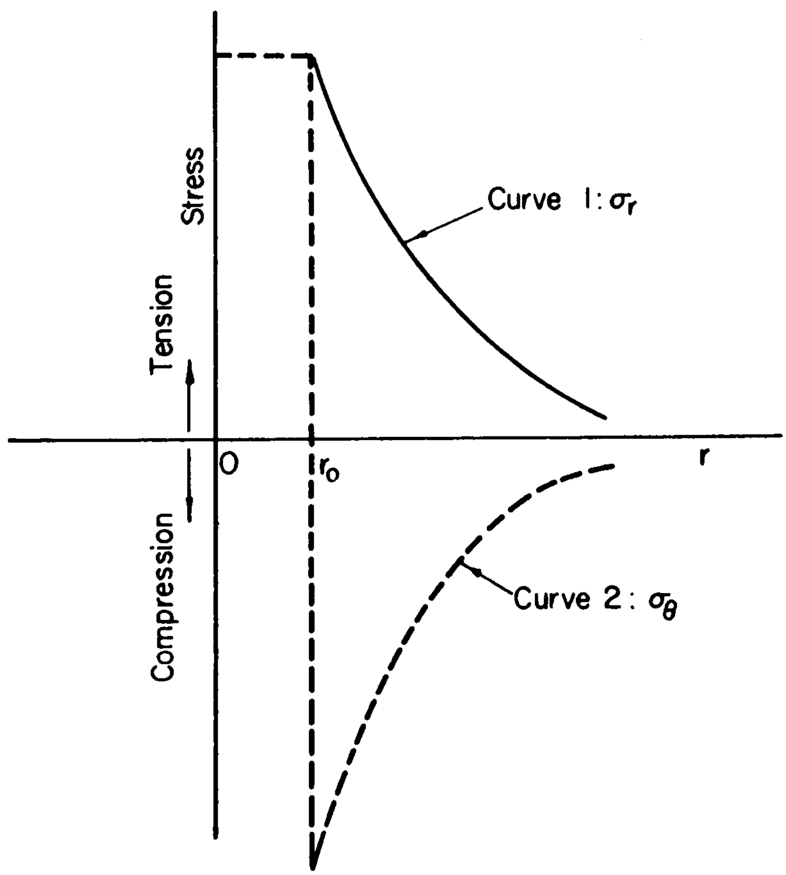
Out-of-flat base plate also can contribute to restraint problems in welding (Ref. 23). As-received materials that are wavy and out-of-flat lead to a condition of misalignment when placed in the welding fixture. Where this condition creates fabrication difficulties it is necessary to flatten the plates. This working when added to the already high level of restraint can increase susceptibility to cracking, or cracking can occur during the flattening operation.

The residual-stress distribution in spot-welded joints is very dependent on the joint pattern or weld pattern used. The simplest case to consider is the residual stress due to a single spot weld. Figure 13 is a schematic representation of the distribution of residual stresses in the area near a single spot weld. The components of stress that are of most concern are those in the radial direction and those in the circumferential direction. The relation between the distance from the weld center and the radial-residual stress is shown by Curve 1 in the figure. Tensile stresses as high as the yield strength of the material may exist in the weld zone. Outside the actual weld zone the tensile residual stress decreases as the distance from the weld area is increased. Curve 2 shows the distribution of the circumferential stress. Again, very high tensile stresses exist within the weld zone; however, outside the weld these stresses are compressive and again fall off as the distance from the weld is increased. From Curve 2 it is apparent that there is an extremely sharp stress gradient around the circumference of any spot weld where the stresses undergo a complete reversal from very high tensile values to high compressive values.

The actual stress distributions in a spot weld in the area very close to the weld are not nearly as simple as shown in Figure 13. Very concentrated stresses often exist in the heat-affected zone close to the original interface of the sheets.




a. Stress Components




b. Relationships Between Radius From the Weld Center, r, and Stresses

FIGURE 13. SCHEMATIC DISTRIBUTION OF RESIDUAL STRESSES AROUND SPOT WELD

When several spot welds are considered instead of just a single spot, the resulting residual-stress patterns are even more complex. An approximate distribution of the residual-stress pattern produced by a series of spot welds can be obtained by the superposition of the residual-stress distributions produced by each weld as shown in the figure. The interaction between the residual stresses accompanying each individual weld becomes significant when the distance between the welds is short – probably at any distance less than four times the diameter of the weld.

The residual stresses in resistance spot welds can be altered by changes in the welding schedule. Changes in heat input, heat pattern, or possible forging action that may be applied through the electrodes are effective. Some information on the effect of such changes in welding parameters on residual stresses has been obtained, but there are many conflicting aspects to this data.

Residual-Stress Effects. For many years there was a trend among engineers to discount the effect of residual stress, since it had been proven that the effect of residual stress is almost negligible when a welded structure fails in a ductile manner. During the last several years much information has been obtained on the effect of residual stress on brittle fracture in steel weldments. It has been found that residual stresses decrease the fracture strength of weldments only when certain conditions are satisfied, but that the loss of strength can be drastic when these conditions are satisfied. A weld failure blamed on residual stress is shown in Figure 14 (Ref. 26). No systematic

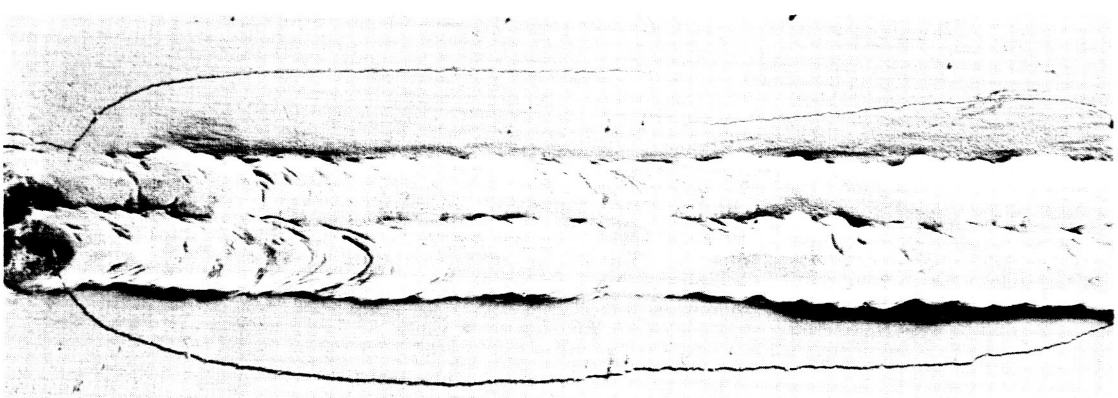


FIGURE 14. FAILURE ATTRIBUTED TO RESIDUAL STRESS IN 2-INCH-THICK INCONEL X AFTER AGING AT 1300 F FOR 20 HOURS (REF. 26)

The base metal was aged prior to welding.

investigation has been made on the effects of residual stresses on fractures in nickel and nickel-base-alloy weldments. The following discussions are based on information on steel weldments and the limited data on nickel-alloy weldments.

In general, the effect of residual stress is significant on fractures that take place at low applied stresses. Observations that have been made on various types of fracture are as follows:

(1) Ductile Fracture – Ductile fracture occurs at high stresses after general yielding. The effect of residual stress on fracture strength is negligible.

(2) Brittle Fracture – When a notch is located in areas where high residual tensile stresses exist, brittle fracture can initiate from the notch at a low applied stress and then propagate through the weldment. Extensive research has been conducted during the last several years on low-stress brittle fracture of steel weldments. No systematic investigations have been made on low-stress brittle fracture of nickel-alloy weldments. Some failures have been observed that indicate that residual stresses may have caused premature failures in nickel-alloy weldments.

(3) Stress-Corrosion Cracking and Hydrogen-Induced Cracking – Stress-corrosion cracking and hydrogen-induced cracking can occur under low applied stresses, even under no applied stress. Residual welding tensile stresses promote the cracking, while residual compressive stresses suppress the cracking.

(4) Fatigue Cracking – The effect of residual stress on fatigue fracture is a controversial subject. Many investigators have reported fatigue-test results that, they claim, were affected by residual stresses. However, others believe that the effect of residual stress on fatigue is not significant.

(5) Buckling Failure – It is known that residual compressive stresses in the base-metal regions around welds may decrease the buckling strength of welded columns and plates.

Stress Relief. There are a number of reasons for reducing or relieving residual stresses associated with welded joints. It is probably necessary to relieve the residual stresses whenever a welded structure is: (1) manufactured to close dimensional tolerances; (2) complex and contains many stress risers; (3) subjected to dynamic loading; (4) subjected to low-temperature service; and (5) subjected to service conditions that might promote stress corrosion. The decision of whether or not to stress relieve and what method to use generally is based on judgment and previous experience.

Residual stresses can be relieved in two ways: (1) thermal-stress-relieving treatments or (2) mechanical-stress-relieving treatments. Occasionally, both treatments are used. Stress relieving can be performed on a finished part or during various stages of processing when dimensional control is a problem.

Thermal-stress-relieving treatments are commonly employed for many materials. These treatments can be combined quite effectively with hot-sizing operations to control both the existing residual stresses and to produce parts to close-dimensional tolerances. Thermal-stress-relieving treatments produce much more uniform changes in the residual-stress patterns than do mechanical-stress-relieving treatments.

Two kinds of heat treatments are used for altering the condition of stresses that may be present in fabricated nickel and nickel-base alloys (Ref. 27):

(1) A stress-relieving heat treatment used to remove or reduce stress in work-hardened non-age-hardenable alloys without producing a recrystallized grain structure. Temperatures range from about 800 to 2200 F, depending on the alloy and its condition.

(2) A stress-equalizing low-temperature heat treatment used to balance stresses in cold-worked material without causing an appreciable decrease in the mechanical strength produced by cold working.

Conditions for stress relieving and stress equalizing several nickel alloys are given in Table III (Ref. 27).

TABLE III. STRESS RELIEVING AND STRESS EQUALIZING OF NICKEL AND SOME NICKEL ALLOYS (REF. 27)

| | Stress Relieving | | | Stress Equalizing | | |
|---|---|---|---|---|---|---|
| Material | Tempera-ture, F | Time at Temperature, hr | Cooling Method | Temperature, F | Time at Temperature, hr | Cooling Method |
| Nickel 200 | 900-1300 | 3-1/2 | Air cool | 500-900 | 2-1 | Air cool |
| Nickel 201 | 900-1300 | 3-1/2 | Ditto | 500-900 | 2-1 | Ditto |
| Nickel 211 | 900-1300 | 3-1/2 | " | 500-900 | 2-1 | " |
| Monel 400 | 1000-1050 | 2-1 | " | 450-600 | 3-1 | " |
| Hastelloy B | 2000-2165 | 1/12 | Air cool or water quench | | Not applicable | |
| Hastelloy C | 2200 | 1/12 | Water quench | | Ditto | |
| Hastelloy R-235 | 1975 | 1/12 | Ditto | | " | |

Mechanical-stress-relieving treatments take on a variety of forms. These include tensile stretching, roll planishing, and peening. With any mechanical-stress-relieving treatment, control of the process is difficult. In addition, the complete removal of residual stresses by mechanical techniques is difficult to accomplish. Mechanical-stress-relieving techniques are most effective in accomplishing a redistribution of residual stresses in a single direction. Effective stress relieving by operations such as roll planishing requires that the weld geometry be very consistent prior to the planishing operation.

## PROCESS SELECTION

Nickel and nickel-base alloys have been joined by most common welding, brazing, and soldering processes. Widespread use has been made of the following processes:

(1) Shielded metal-arc welding
(2) Gas tungsten-arc welding
(3) Gas metal-arc welding
(4) Electron-beam welding

(5) Resistance spot, roll spot, and seam welding
(6) Brazing and soldering.

Limited use has been made of many other joining processes including:

(1) Arc spot welding
(2) Plasma welding
(3) Diffusion welding
(4) Roll welding
(5) Pressure gas welding
(6) Flash welding.

Other processes also have been used that will not be discussed here. Excluded from this report are oxyacetylene, oxy-fuel gas, and air-fuel gas-fusion welding. These processes are rarely, if ever, used for new applications such as aerospace products. Table IV shows the joining processes used for nickel and nickel-base alloys.

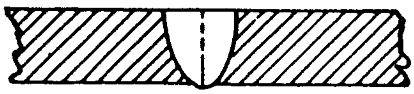
As with many other metals, selection of a joining process for nickel and nickel-base alloys often is influenced by the physical characteristics of the part to be joined. Fortunately, the varied characteristics of joining processes lead to a very broad range of possible applications. Most joints in nickel and nickel-base alloys can be made by several different joining processes. However, welding finds major usage in subassembly fabrication and many large structural components. Cost, available equipment, maintenance, reliability, accessibility, thickness, and overall component size also are important factors in assessing the proper usage of welding and alternative joining methods.

Joint design also can influence the selection of the joining process. Design can limit the number of potentially usable processes and exclude those processes that are either not usable or would be very difficult to adapt for the particular application. Figure 15 illustrates several joint designs and lists the processes that normally would or would not be used for joining; it is apparent that several processes can be selected for making each joint when considered from a pure capability viewpoint. Other factors reviewed earlier may reduce the number of potentially useful processes to a fewer number than those indicated.

TABLE IV. JOINING PROCESSES APPLICABLE TO NICKEL AND SOME TYPICAL NICKEL-BASE ALLOYS[a]

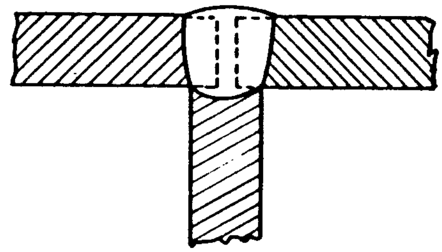
| Alloy | Shielded Metal Arc | Gas Tungsten Arc | Gas Metal Arc | Arc Spot | Submerged Arc | Plasma Arc | Electron Beam | Resistance Spot | Roll Resistance Spot | Resistance Seam | Flash | Diffusion | Deformation | Brazing | Soldering | Gas | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| High-Nickel Alloys | | | | | | | | | | | | | | | | | |
| Nickel 200 | X | X | X | -- | X | -- | X | X | X | X | X | -- | X | X | X | X | 8, 9, 28 |
| Dispersion-Strengthened Nickel | | | | | | | | | | | | | | | | | |
| TD nickel | -- | X | -- | -- | -- | -- | X | X | -- | -- | X | X | -- | X | -- | -- | 4, 29 |
| Solid-Solution-Hardening Alloys | | | | | | | | | | | | | | | | | |
| Monel 400 | X | X | X | -- | X | -- | -- | X | X | X | X | -- | X | X | X | X | 9, 16 |
| Inconel 600 | X | X | X | -- | X | -- | X | X | X | X | X | -- | X | X | X | X | 9, 15, 28 |
| Hastelloy B | X | X | X | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | 8 |
| Hastelloy X | X | X | X | -- | -- | -- | -- | X | X | X | -- | -- | -- | -- | -- | -- | 8 |
| Precipitation-Hardening Alloys | | | | | | | | | | | | | | | | | |
| Monel K-500 | X | X | X | -- | -- | -- | -- | X | X | X | X | -- | X | X | X | X | 9 |
| Inconel X-750 | X | X | X | -- | -- | -- | -- | X | X | X | X | -- | X | X | X | -- | 2, 9 |
| Nimonic 80A | -- | X | X | -- | X | -- | -- | X | -- | X | -- | -- | -- | -- | -- | -- | 1, 2 |
| Udimet 500 | -- | X | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | -- | |
| Waspaloy | X | X | -- | -- | -- | -- | -- | X | -- | X | -- | -- | -- | -- | -- | -- | 2 |
| René 41 | -- | X | -- | X | -- | -- | X | X | -- | X | X | -- | -- | X | -- | -- | 2, 28, 30 |

(a) X indicates that the process has been used for joining but is not necessarily the best joining method; -- indicates that the process is seldom, if ever, used for joining the alloy. Contact the producer for latest information.



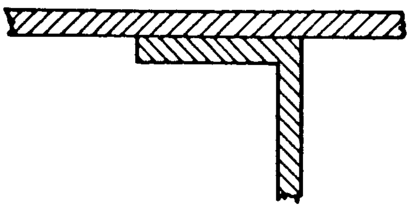
a. Butt Joint

Select: TIG, MIG, electron beam, flash, pressure gas
Exclude: resistance spot and seam
Consider: plasma, high frequency



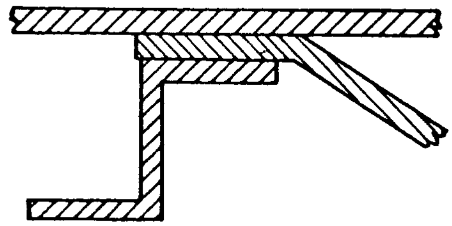
b. Fabricated Tee

Select: TIG, MIG, electron beam
Exclude: flash, resistance spot and seam
Consider: plasma, high frequency, solid state



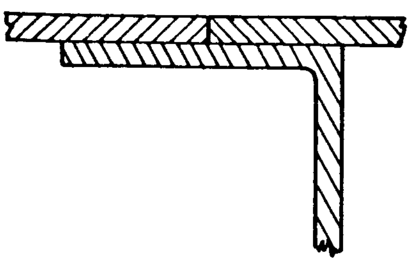
c. Sheet-Stringer Lap

Select: resistance spot or seam arc spot, solid state
Exclude: flash, pressure
Consider: electron beam, plasma



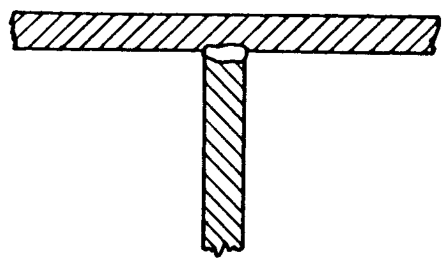
d. Multilayer Lap

Select: resistance or arc spot or seam, solid state
Exclude: flash, pressure gas
Consider: electron beam, plasma



e. Sheet Splice With Doubler

Select: resistance or arc spot or seam, solid state
Exclude: flash, pressure gas
Consider: electron beam, plasma



f. Cap or Tee

Select: electron beam, TIG, MIG, high frequency
Exclude: flash, arc and resistance spot
Consider: solid state, resistance seam

FIGURE 15. TYPICAL WELD JOINTS IN NICKEL AND NICKEL-BASE ALLOYS

The relationship of joining to other fabrication operations is an important aspect in process selection. A simplified subassembly-process flow chart illustrates some of the possibilities. The part used as an example is a contoured stiffened skin too large to make from a single sheet. The materials involved are skin sheets and formed stiffeners as sketched in Figure 16. The flow chart, Figure 17, shows that many possible approaches might be used to fabricate this single part. The important point here is to remember that the fabrication operations immediately before and after joining are closely related to successful part fabrication. Good joint fitups are needed and all parts must be properly cleaned before joining. Stress relieving of weldments immediately after welding is sometimes essential.

## JOINING PROCESSES

Many joining processes can be used successfully for joining nickel and nickel-base alloys. Discussions of joining processes are presented in three major sections:

(1) Fusion welding
(2) Solid-state welding
(3) Brazing and soldering.

Discussions of fusion welding include those joining processes in which substantial amounts of molten metal are normally produced during the joining operation. Discussions of solid-state bonding are limited to those processes in which molten metal is not produced. Some processes, such as resistance spot welding and flash welding, can rightfully be included within each of these discussions. Such processes are described in accordance with their conventional use. Brazing and soldering are conventional processes and are discussed separately. Processes not included are gas welding, adhesive bonding, mechanical fastening, and various other specific welding processes. Adhesive bonding and mechanical fastening of nickel and nickel-base alloys have been covered in other reports in this series (Refs. 31, 32).

### FUSION WELDING

This section describes joining processes in which substantial amounts of molten metal are produced during the joining operation.

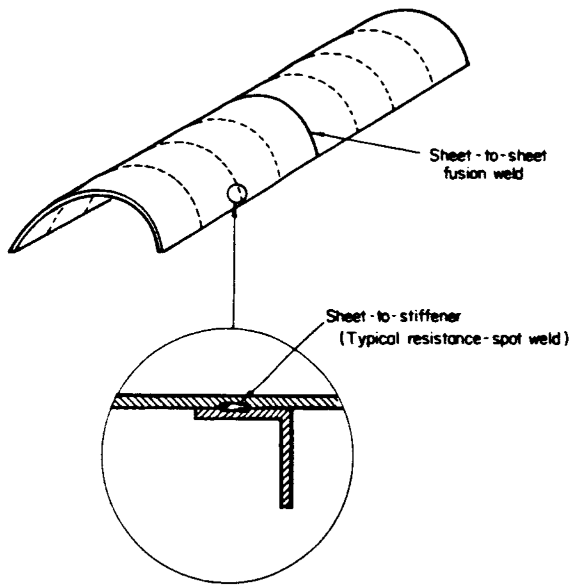



FIGURE 16. STIFFENED-SKIN COMPONENT

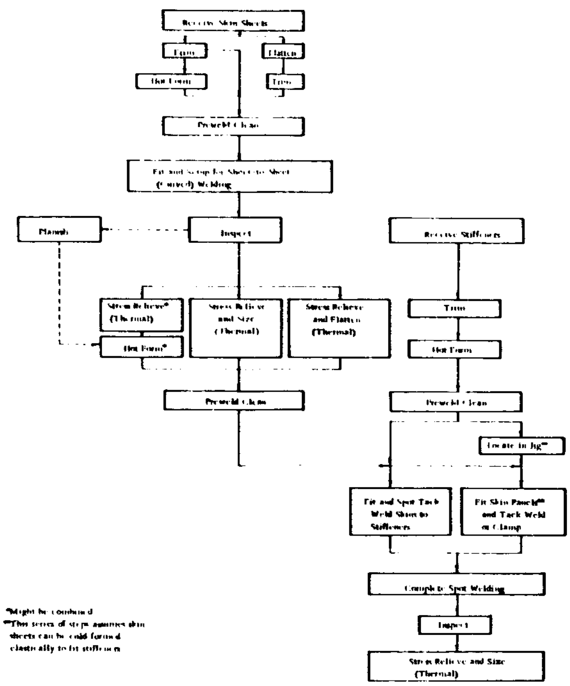



FIGURE 17. FLOW CHART SHOWING POSSIBLE RELATION OF WELDING TO OTHER OPERATIONS

The arc-welding processes typically involve the melting of filler metal, base metal, or both. Other processes, such as flash welding and high-frequency resistance welding produce molten metal during the joining cycle but, often, little or no evidence of molten metal remains in the completed joint. When used in a conventional manner, molten metal also is produced with resistance spot- and seam- and roll resistance spot-welding processes. Spot welding also has been used to make solid-state welds. Fusion-welding processes for joining of nickel and nickel-base alloys are discussed in the following.

Shielded Metal-Arc Welding. Shielded metal-arc welding is used extensively for joining nickel and some nickel-base alloys. It is applicable to a wide range of base-metal thicknesses, and it is adaptable to manual, semiautomatic, or fully automatic operations. As thickness decreases, other processes offer important advantages.

In shielded metal-arc welding, the heat required to melt the filler metal and joint edges is provided by an arc between a covered metal electrode and the work. Electrode coverings perform various functions (Ref. 33).

(1) Produce a gas that shields the arc from the atmosphere

(2) Promote electrical conduction across the arc

(3) Add slag-forming materials to the weld pool for the purpose of refining the molten metal and, in some cases, of adding alloying elements

(4) Provide materials for the purpose of controlling bead shape.

Figure 18 is a schematic representation of the process (Ref. 33). Metal is transferred from the electrode to the work in the form of large drops or in the form of a spray of small drops. Generally, both modes of transfer occur.

Shielded-metal-arc-welding techniques for some nickel and nickel-base alloys are similar to those used for steel, and can be used in all positions. These alloys, however, are not as fluid as mild steel and low-alloy steel. The weld joints should be wide enough to permit easy deposition of stringer passes. Excessive agitation or puddling of the weld pool can result in serious loss of alloying or

refining elements. In addition, penetration with high-nickel alloys is shallower than for steel; however, high-heat-input rates to increase penetration also can result in loss of some alloying elements.

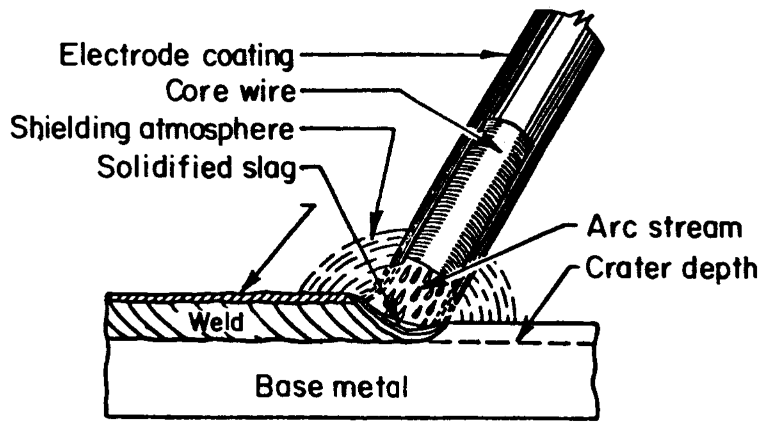



FIGURE 18. SCHEMATIC REPRESENTATION OF THE SHIELDED-METAL-ARC-WELDING PROCESS (REF. 33)

Some nickel-base alloys require techniques that differ from those used for steel. Welding operators familiar with techniques for joining steel require considerable additional training to enable them to produce nuclear-quality welds for example, with Inconel (Ref. 34).

Equipment. Conventional equipment is used for shielded metal-arc welding of nickel and nickel-base alloys. There are no preferred specific types of welding equipment that offer improved welding characteristics or weld properties. However, direct-current power sources and reversed polarity are recommended.

The welding current that may be used satisfactorily with covered electrodes depends on the type of electrode, size, and sheet thickness. Other variables such as the type of backing groove, backing material, clamping, and joint design also can affect current requirements and, in turn, determine the size of electrode to use.

Materials. High-purity, high-nickel, and solid-solution-hardening alloys are all welded with this process. There are some exceptions, but covered electrodes are available commercially for most of these nickel and nickel-base alloys. These electrodes are classified according to the chemical composition of the deposited weld metal as shown in Table V (Ref. 35). They are usually selected to match the composition of the base metal.

TABLE V. CHEMICAL-COMPOSITION REQUIREMENTS FOR WELD METAL DEPOSITED FROM NICKEL AND NICKEL-BASE-ALLOY-COVERED WELDING ELECTRODES (REF. 35)

| AWS-ASTM Classification | Carbon | Manganese | Iron | Phosphorus | Sulfur | Silicon | Copper | Nickel | Cobalt | Aluminum | Titanium | Chromium | Columbium Plus Tantalum | Molybdenum | Vanadium | Tungsten | Other Elements total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ENi-1 | 0.10 | 0.75 | 0.75 | -- | 0.020 | 1.25 | 0.25 | 92.0 min[a] | -- | 1.0 | 1.0-4.0 | -- | -- | -- | -- | -- | 0.50 |
| ENiCu-1 | 0.15 | 4.0 | 2.5 | -- | 0.025 | 1.25 | Bal | 62.0-70.0[a] | -- | 1.0 | 1.5 | -- | 3.0 | -- | -- | -- | 0.50 |
| ENiCu-2 | 0.15 | 6.0 | 2.5 | -- | 0.025 | 1.5 | Bal | 60.0-68.0[a] | -- | 1.0 | 1.0 | -- | 2.5 | -- | -- | -- | 0.50 |
| ENiCu-3 | 0.45 | 4.0 | 2.5 | -- | 0.025 | 1.25 | Bal | 60.0-68.0[a] | -- | 1.0-4.0 | 1.0 | -- | -- | -- | -- | -- | 0.50 |
| ENiCu-4 | 0.40 | 4.0 | 2.5 | -- | 0.025 | 1.0 | Bal | 62.0-70.0[a] | -- | 1.5 | 1.0 | -- | -- | -- | -- | -- | 0.50 |
| ENiCr-1 | 0.15 | 1.5 | 4.0 | -- | 0.015 | 0.75 | 0.50 | 70.0 min[a] | -- | -- | -- | 17.5 min | 1.5-4.0 | -- | -- | -- | 0.50 |
| ENiCrFe-1 | 0.08 | 1.5 | 11.0 | -- | 0.015 | 0.75 | 0.50 | 68.0 min[a] | -- | -- | -- | 13.0-17.0 | 1.5-4.0 | -- | -- | -- | 0.50 |
| ENiCrFe-2 | 0.10 | 1.0-3.5 | 6.0-12.0 | -- | 0.020 | 0.75 | 0.50 | Bal | -- | -- | -- | 13.0-17.0 | 0.5-3.0 | 0.50-2.50 | -- | -- | 0.50 |
| ENiCrFe-3 | 0.10 | 5.0-9.5 | 6.0-10.0 | -- | 0.015 | 1.0 | 0.50 | Bal | (b) | -- | 1.0 | 13.0-17.0 | 1.0-2.5[c] | -- | -- | -- | 0.50 |
| ENiMo-1 | 0.12 | 1.0 | 4.0-7.0 | 0.040 | 0.030 | 1.0 | -- | Bal | 2.5 | -- | -- | 1.0 | -- | 26.0-30.0 | 0.60 | -- | 0.50 |
| ENiMo-2 | 0.12 | 1.0 | 4.0-7.0 | 0.040 | 0.030 | 1.0 | -- | Bal | 2.5 | -- | -- | 14.5-16.5 | -- | 15.0-18.0 | 0.35 | 3.0-4.5 | 0.50 |
| ENiMo-3 | 0.12 | 1.0 | 4.0-7.0 | 0.040 | 0.030 | 1.0 | -- | Bal | 2.5 | -- | -- | 2.5-5.5 | -- | 23.0-27.0 | 0.60 | -- | 0.50 |

(a) Includes incidental cobalt.
(b) Cobalt - 0.12 max when specified.
(c) Tantalum - 0.25 max when specified.

It should be noted that many electrode coatings contain hygroscopic materials. Their containers should remain sealed until needed for use. Once the containers are opened, the electrodes should be stored in a moisture-free area.

Welding Conditions and Weld Properties. Shielded-metal-arc-welding conditions depend on several factors. Alloy composition, electrode type, material thickness, and tooling affect welding conditions. Although recommended welding conditions are readily available from equipment and material suppliers, it is difficult to establish strict rules regarding welding conditions. Often this is not necessary. For example, various combinations of current, voltage, and welding speed will provide satisfactory welds for a specific material thickness and joint design.

The heat effects produced by metal-arc welding nickel, Monel, and Inconel are not considered harmful. Grain growth and softening occurs in the heat-affected zones, but there is no noticeable alteration in ductility or strength. Some properties of shielded metal-arc welds in nickel and nickel-base alloys are given in Table VI (Ref. 8).

When welding for high-temperature service, it is important to remove all flux or slag from all weld passes and from the completed weldment. The slag may not be corrosive at low temperatures, but severe attack may occur at elevated operating temperatures.

Applications. Shielded metal-arc welding is used for fabricating nickel and many nickel-base alloys. Some typical applications are described in the following.

Nuclear-Reactor Components. Shielded metal-arc welding has been used for joining nuclear-reactor components (Refs. 34, 36). Welds for nuclear-reactor applications must be of extremely high quality and essentially free from defects. Unusually heavy sections often must be welded.

Shielded metal-arc welding was used for finishing joints in a 2-inch-thick Inconel reactor pressure vessel because of the high deposition rates available with this process (Ref. 34). Porosity and slag inclusions were minimized by baking the covered electrodes and by interpass cleaning. Root passes for this vessel were made using the gas tungsten-arc process. Also, to meet the need for defect-free welds, a new covered welding electrode, MIL-4N85, was developed (Ref. 36). The operating characteristics of this electrode

TABLE VI. MECHANICAL PROPERTIES OF SHIELDED METAL-ARC WELDS IN NICKEL AND NICKEL-BASE ALLOYS[a] (REF. 8)

| Alloy | Thickness, in. | Groove Type | Electrode Diameter, in. | Average Tensile Strength[b], psi | Minimum Elongation (Free Bend), per cent | Condition |
|---|---|---|---|---|---|---|
| Nickel 200 | 1/8 | Square | 3/32 | 69,900 | 25 | -- |
| | 11/16 | Single vee | 5/32 | 77,400 | 25 | -- |
| Monel 400 | 1/8 | Square | 3/32 | 78,600 | 30 | -- |
| | 3/4 | Double vee | 5/32 | 84,400 | 30 | -- |
| Monel K-500[c,d] | 1/8 | Square | 5/32 | 129,900[a] | 19 | -- |
| | 3/8 | Single vee | 5/32 | 121,400[a] | 4 | -- |
| Inconel X-750[c,d] | 3/8 | Single U | 5/32 | 99,500/ 106,000 | 27 | As welded |
| | | | | 167,200/ 169,000 | 24 | Age only |
| | | | | 161,000 | 25 | Quench and age[e] |
| Hastelloy B | 1/8 | Square | 3/32 | 117,500 | -- | -- |
| | 3/8 | Double vee | 5/32 | 112,600 | -- | -- |
| Hastelloy C | 1/8 | Square | 3/32 | 114,000 | -- | -- |
| | 3/8 | Double vee | 5/32 | 112,600 | -- | -- |
| Hastelloy F | 5/64 | Square | 3/32 | 104,900 | -- | -- |
| Hastelloy N | 1/16 | Square | -- | 116,100 | -- | -- |
| Hastelloy X | 3/32 | Square | -- | 110,300 | -- | -- |
| | 3/8 | Double vee | | 108,700 | -- | -- |

(a) Flat position.
(b) Reduced section short gage length.
(c) Actual values.
(d) Aging treatments: Monel K-500, 1100 F, 16 hr, air cool; Inconel X-750, 1300 F, 6 hr, air cool.
(e) 2000 F, 6 hr, water quench.

are excellent, and the slag is easily removed from welds deposited in all positions. The electrode has produced crack-free and porosity-free welds in all positions and under high restraint in Inconel.

Press Roll. Shielded metal-arc welding of a large Monel 400 press roll is shown in Figure 19 (Ref. 9). The roll was fabricated from three 2-3/4-inch-thick plates, 38 inches wide by 240 inches long, that were welded together using Monel Welding Electrode 130 covered electrodes. High deposition rates were needed to deposit 700 pounds of filler metal.

Metal-arc welding is one of the most common processes used for welding Hastelloy alloys, and it is used in welding all grades except Hastelloy D (Ref. 37). Direct current with reversed polarity is generally employed. When joint design permits, rapid travel with as little "weaving" as possible is preferred, in order to minimize heat. The Hastelloy alloys have a tendency to boil, which causes porosity in the welds. Overheating may occur in the starting and stopping of the bead. To avoid this, minimum currents that are consistent with the thickness or size of the parts should be used. It is occasionally desirable to strike the arc on a tab adjacent to the weld joint when starting the weld, and to run the electrode off to the side of the joint when stopping. Because of the fluidity of these alloys, position welding is somewhat difficult. Therefore, whenever possible, welding should be done in the down-hand position. The inlet cooling sleeve shown in Figure 20 is a typical application for metal-arc welding these alloys (Ref. 37).

Gas Tungsten-Arc Welding. The gas tungsten-arc process is used extensively for joining nickel and nickel-base alloys. It is particularly suited for joining of very thin materials and adaptable to a manual, semiautomatic, or fully automatic operation. It can, however, be used on almost any thickness; but as the thickness increases above 0.1 inch other fusion-welding processes offer important advantages. "TIG welding" and "tungsten inert-gas welding" are familiar synonyms for the process.

In gas tungsten-arc welding, the heat required to melt the joint edges is supplied by an arc between a tungsten electrode in the welding torch and the workpiece. The arc, electrode, and hot metal are protected from air by a flow of inert gas such as argon, helium, or argon-helium mixtures around the tungsten electrode. In many instances supplementary shielding to protect the hot metals from

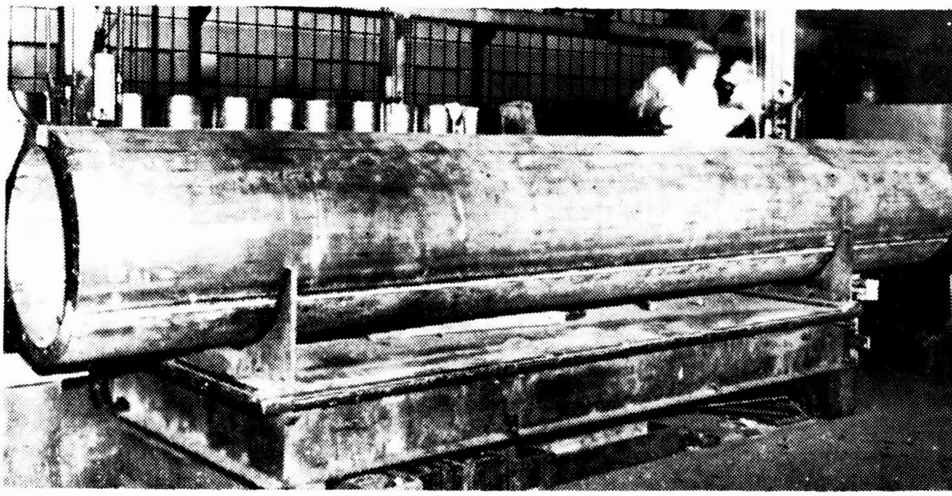


FIGURE 19. SHIELDED METAL-ARC WELDING OF A MONEL PRESS ROLL (REF. 9)

FIGURE 20. SHIELDING METAL-ARC WELDING OF A HASTELLOY INLET COOLING SLEEVE (REF. 37)

contamination is provided by trailing shields, underbead shields, side shields, or by welding within a gas-filled chamber.

Gas tungsten-arc welds can be made with the addition of filler metal or without the addition of filler metal. Whether filler metal is or is not added depends on such factors as joint design, joint thickness, availability of suitable filler metals, and desired weld characteristics. Gas tungsten-arc welds are often made by melting only the edges of the parts to be joined. Filler metal is always added when the joint contains a groove or similar preparation and, in some instances, to joints that are not grooved. The addition of filler metal to square-butt joints, for example, increases the tolerance of gas tungsten-arc welding for slight variations in the joint fitup.

Gas tungsten-arc welding of nickel and nickel-base alloys has been performed in all welding positions. When welding in other than the flat position, changes in the shielding afforded by the inert gases should be anticipated.

Equipment. Conventional gas tungsten-arc power supplies, torches, and control systems are used for welding nickel and nickel-base alloys. The process is illustrated in Figure 21 (Ref. 38). No significant changes in welding characteristics or weld properties have been reported that can be attributed to the use of any specific type of welding equipment. However, welding techniques for some nickel-base alloys differ from techniques for other metals; welding operators may require retraining to enable them to produce high-quality welds. High-frequency arc starting is used to avoid tungsten inclusions that are often found with touch-starting techniques.

Nickel and nickel-base alloys can be welded very successfully in open-air atmospheres with the right supplemental equipment. The inert-gas flowing from a conventional gas-tungsten-arc welding torch may not provide complete protection from contamination during welding. Auxiliary trailing shields attached to the welding torch, or auxiliary underbead- or side-shielding devices built into the weld tooling are used when improved shielding is needed. The importance of tooling to assist in weld shielding was discussed earlier in the section on inert-gas shielding. Figure 22 illustrates a commonly used type of combined torch-trailing shield arrangement. Such shields are designed to supply a uniform nonturbulent flow of inert gas over the weld as it cools behind the torch. It is much easier to

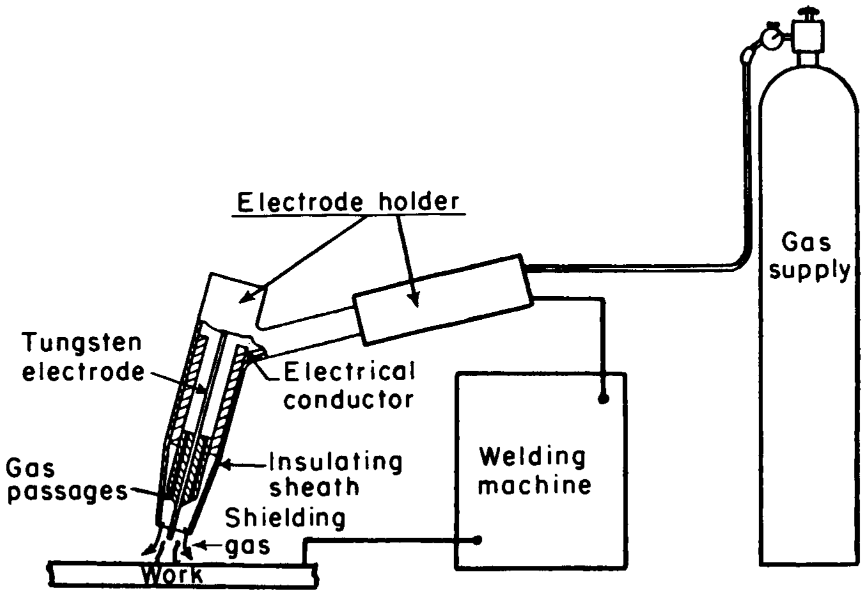



FIGURE 21. GAS-TUNGSTEN-ARC-WELDING PROCESS (REF. 38)

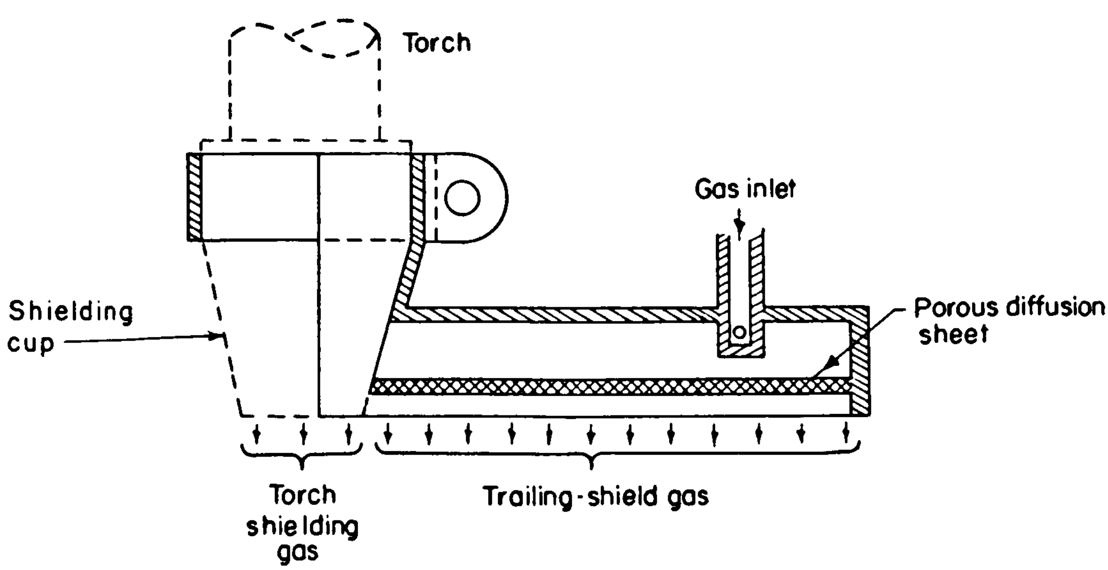



FIGURE 22. ILLUSTRATION OF A COMBINATION TORCH-TRAILING-SHIELD ARRANGEMENT

insure good shielding during mechanized gas-tungsten-arc welding than in manual operations. Mechanized welding operations are recommended and used wherever possible in welding nickel and nickel-base alloys.

The shielding chambers used for gas tungsten-arc welding nickel can be of several basic designs as was illustrated earlier in the section on tooling. Inert gases replace the air by evacuating and backfilling the chamber, by flow purging or by collapsing the chamber and backfilling. Shielding chambers are used when welding nickel parts that cannot be protected satisfactorily in the open atmosphere. Precautions need to be taken to prevent leakage of air, water vapor, or water into the chambers.

The gases used for shielding include helium, argon, and argon-helium mixtures. Helium, however, has definite advantages over argon for simple fusion welding of thin sheet material (Ref. 9):

(1) Porosity-free joints are more readily obtained in Monel 400 and less fine porosity is obtained in Nickel 200.

(2) Increased welding speeds can be obtained.

Electrodes for gas tungsten-arc welding nickel and nickel-base alloys consist of tungsten, tungsten-thoria, or tungsten-zirconium. These electrodes normally are operated on straight-polarity direct current, although alternating current may be used. The electrodes usually are ground to a sharp point (Ref. 8).

Experience shows that weld-metal contamination by tungsten is less with the tungsten-thoria electrodes. Chemical compositions of conventional gas-tungsten-arc-welding electrodes are given in Table VII (Ref. 39). Extension of the electrode beyond the shielding

TABLE VII. CHEMICAL COMPOSITIONS OF GAS-TUNGSTEN-ARC WELDING ELECTRODES (REF. 39)

| AWS-ASTM Classification | Tungsten (Minimum), per cent | Thorium, per cent | Zirconium, per cent | Total Other Elements (Maximum), per cent |
|---|---|---|---|---|
| EWT | 99.5 | -- | -- | 0.5 |
| EWTh-1 | 98.5 | 0.8 to 1.2 | -- | 0.5 |
| EWTh-2 | 97.5 | 1.7 to 2.2 | -- | 0.5 |
| EWZr | 99.1 | -- | 0.3 to 0.5 | 0.5 |

cup should be as short as possible. This practice helps provide more effective gas shielding.

The equipment used to drive the welding filler wire should provide uniform filler-metal feed rates. Feed rates should be as uniform as possible with both manual and machine wire feeding to prevent localized weld irregularities that may contribute to cracking. Even the best quality welding wire can be contaminated by foreign material, such as lubricating oils, that may become lodged in the wire-feed equipment. Periodic checks should be made to be sure that oil and other foreign material is not present in the drive system or guide components.

Materials. All of the nickel-base alloys that are weldable have been joined with the gas-tungsten-arc welding process. Commercially pure nickel and many of its alloys can be welded readily. The filler-metal composition that is used for a particular alloy is determined by service requirements. The filler metal and base metal should be selected very carefully, particularly where corrosion is likely to be a major factor in service. Usually, the filler metal is selected to match the composition as closely as possible. Departures from this practice are often necessary for some alloys. For welds of very short length, cut and straightened lengths of filler wire may be used instead of continuous coils. For manual gas tungsten-arc welding, sheared strips of a base-metal sheet are sometimes used as filler wire. Consumable filler-metal inserts also can be used to assist in welding root passes. On rare occasions, a similar procedure is used in mechanized welding when a preplaced strip of sheet or wire is inserted in the joint to serve as a filler metal. Care is recommended when using this procedure because of the difficult handling and potential contamination problems involved. Filler metals used for gas tungsten-arc welding some nickel-base alloys are listed in Table VIII. (Ref. 40). These filler metals are classified on the basis of as-manufactured chemical composition. They can be used for gas metal-arc and submerged arc welding where applicable.

Joint designs for gas tungsten-arc welding of nickel and nickel-base alloys are similar to those used for shielded metal-arc welding. Typical joint designs were shown in Figure 1.

Welding Conditions. Welding conditions are dependent on material thickness, joint design, the type of weld tooling being

TABLE VIII. CHEMICAL-COMPOSITION REQUIREMENTS FOR NICKEL AND NICKEL-BASE-ALLOY BARE WELDING RODS AND ELECTRODES (REF. 40)

| AWS-ASTM Classification | Carbon | Manganese | Iron | Sulfur | Silicon | Copper | Nickel Plus Cobalt[a] | Co-balt | Aluminum | Titanium | Chromium | Columbium Plus Tantalum | Molybdenum | Vanadium | Tungsten | Other Ele-ments, total |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| RNi-2 | 0.15 | 0.35 | 0.4 | 0.01 | 1.0 | 0.25 | 97.0 min | -- | -- | 0.50 | -- | -- | -- | -- | -- | 0.50 |
| ERNi-3 | 0.15 | 1.0 | 1.0 | 0.01 | 0.75 | 0.25 | 93.0 min | -- | 1.5 | 2.0-3.5 | -- | -- | -- | -- | -- | 0.50 |
| RNiCu-5 | 0.30 | 2.0 | 2.5 | 0.02 | 0.50 | Bal | 63.0-70.0 | -- | -- | -- | -- | -- | -- | -- | -- | 0.50 |
| RNiCu-6 | 0.30 | 1.0 | 1.0 | 0.02 | 0.50-1.50 | Bal | 55.0-60.0 | -- | -- | -- | -- | -- | -- | -- | -- | 0.50 |
| ERNiCu-7 | 0.15 | 4.0 | 2.5 | 0.02 | 1.25 | Bal | 62.0-69.0 | -- | 1.25 | 1.5-3.0 | -- | -- | -- | -- | -- | 0.50 |
| ERNiCu-8 | 0.25 | 1.5 | 2.0 | 0.01 | 1.0 | Bal | 63.0-70.0 | -- | 2.0-4.0 | 0.25-1.00 | -- | -- | -- | -- | -- | 0.50 |
| ERNiCr-2 | 0.08-0.15 | 1.0 | 3.0 | 0.015 | 0.30 | 0.50 | 75.0 min | -- | 0.40 | 0.15-0.50 | 19.0-21.0 | -- | -- | -- | -- | 0.50 |
| ERNiCr-3 | 0.10 | 2.5-3.5 | 3.0 | 0.015 | 0.50 | 0.50 | 67.0 min | (b) | -- | 0.75 | 18.0-22.0 | 2.0-3.0[c] | -- | -- | -- | 0.50 |
| RNiCrFe-4 | 0.10 | 1.0 | 6.0-10.0 | 0.015 | 0.50 | 0.50 | 72.0 min | -- | -- | -- | 14.0-17.0 | -- | -- | -- | -- | 1.00 |
| ERNiCrFe-5 | 0.08 | 1.0 | 6.0-10.0 | 0.015 | 0.35 | 0.50 | 70.0 min | -- | -- | -- | 14.0-17.0 | 1.5-3.0 | -- | -- | -- | 1.00 |
| ERNiCrFe-6 | 0.08 | 2.0-2.7 | 10.0 | 0.015 | 0.35 | 0.50 | 67.0 min | -- | -- | 2.5-3.5 | 14.0-17.0 | -- | -- | -- | -- | 0.50 |
| ERNiCrFe-7 | 0.08 | 1.0 | 5.0-9.0 | 0.01 | 0.50 | 0.50 | 70.0 min | -- | 0.40-1.00 | 2.00-2.75 | 14.0-17.0 | 0.70-1.20 | -- | -- | -- | 0.50 |
| ERNiMo-4 | 0.08 | 1.0 | 4.0-7.0 | 0.03 | 1.0 | -- | Bal | 2.5 | -- | -- | 1.0 | -- | 26.0-30.0 | 0.20-0.60 | -- | 0.50 |
| ERNiMo-5 | 0.08 | 1.0 | 4.0-7.0 | 0.03 | 1.0 | -- | Bal | 2.5 | -- | -- | 14.5-16.5 | -- | 15.0-17.0 | 0.35 | 3.0-4.5 | 0.50 |
| ERNiMo-6 | 0.12 | 1.0 | 4.0-7.0 | 0.03 | 1.0 | -- | Bal | 2.5 | -- | -- | 4.0-6.0 | -- | 23.0-26.0 | 0.60 | -- | 0.50 |

Note: Single values shown are maximum percentages except where noted otherwise.

(a) Cobalt, if determined, 1.00 per cent maximum.
(b) Cobalt, 0.10 maximum when so specified.
(c) Tantalum, 0.30 maximum, when so specified.

used, and whether manual or machine welds are made. Also, for any given thickness and joint design various combinations of amperage, voltage, welding speed, and filler-wire feed speed are satisfactory. As a result, no hard and fast rules can be specified for welding conditions. Table IX lists welding conditions for several nickel and nickel-base alloys.

Welding conditions generally do not have to be adjusted radically to accommodate the various nickel-base alloys, but they are often adjusted as a means of controlling weld porosity.

Tack welding is used to preposition detail parts or subassemblies for final welding operations. Elaborate fixturing often can be eliminated when tack welds are used to their full advantage. Various tack-welding procedures are used, but good cleaning practices and adequate shielding are provided to prevent contamination of the welds. Contamination or cracks developed in tack welds can be transferred to the completed weld. One procedure is to perform tack welding in such a way that the finished weld never crosses over a previous tack weld. To accomplish this, sufficient filler metal is used in tack welding to completely fill the joint at a particular location. The final weld beads are blended into each end of the tack welds.

Properties. A large number of joint properties have been determined for gas tungsten-arc welds in nickel and nickel-base alloys. The properties measured by static tension, notch tension, bend and crack susceptibility tests compare very favorably with parent-metal properties. Properties of gas tungsten-arc welds in nickel and nickel-base alloys can vary depending on the condition of the base metal, postweld heat treatments, and service conditions. Fatigue tests have been carried out on gas tungsten-arc welded Nimonic 80A and Nimonic 90 at room temperature and at elevated temperatures (Ref. 1). The strength for both conditions was higher at elevated temperatures than at room temperature. The increase in fatigue strength at elevated temperatures is attributed tentatively to strain-induced precipitation. Information also is available on the effects of postweld heat treatments on weld properties for a limited number of alloys. Some typical properties are given in Table X.

Applications. Gas tungsten-arc welding is used for joining all types of nickel-base alloys as was shown in Table IV. Some typical applications for gas tungsten-arc welding are discussed in the following sections.

TABLE IX. CONDITIONS FOR GAS TUNGSTEN-ARC WELDING SELECTED NICKEL-BASE ALLOYS

| Base Metal and Thickness, in. | Filler Metal and Wire Diameter, in. | Electrode and Size, in. | Groove Type | Number of Passes | Welding Speed, ipm | Wire-Feed Speed, ipm | Arc Voltage, volts | Current, Amperes, and Polarity | Shielding Gas and CFH Flow Rate: Torch | Shielding Gas and CFH Flow Rate: Trailing | Shielding Gas and CFH Flow Rate: Backup | Remarks | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Hastelloy B, 0.020 | None | Th-W, 0.062 | -- | -- | 8 | None | 25 | 8 DCSP | He/50 | -- | He/50 | -- | -- |
| Inconel 718, 0.025 | None | Th-W, 0.062 | -- | -- | 9 | None | 16 | 12 DCSP | He/50 | -- | He/50 | -- | -- |
| Inconel X, 0.025, 1.5 | Inconel 69, 0.063 | Th-W, 0.062 | -- | -- | -- | -- | -- | -- DCSP | --/20 | -- | -- | Manual | 41 |
| | AWS ERN 69, 0.062 | W, 0.094 | Double U | -- | -- | -- | 20 | 100-200, DCSP | He/20 | -- | A/10 | Manual | 14 |
| Hastelloy R-235, 0.020, 0.040 | -- | Th-W, 0.040 | -- | -- | 15 | -- | 10 | 30 DCSP | A/16 | -- | A/16 | -- | 42 |
| | -- | Th-W, 0.062 | -- | -- | 30 | -- | 10 | 50 DCSP | 17A-83He/50 | -- | A/20 | -- | 42 |

TABLE X. MECHANICAL PROPERTIES OF GAS TUNGSTEN-ARC WELDS IN NICKEL AND NICKEL-BASE ALLOYS[(a)]

| Alloy | Thickness, in. | Groove Type | Electrode Diameter, in. | Average Tensile Strength, $10^3$ psi | Minimum Elongation (Free Bend), per cent | Joint Efficiency, per cent | Condition | Reference |
|---|---|---|---|---|---|---|---|---|
| Nickel 200 | 1/8 | Square butt | -- | 66.5 | 40 | -- | -- | 8 |
| Monel 400 | 1/8 | Ditto | -- | 81.7 | 35 | -- | -- | 8 |
| Inconel 600 | 1/8 | " | | 94.7 | 31 | -- | -- | 8 |
| Hastelloy B | 1/8 | " | 3/32 | 118.5 | 36 | -- | -- | 8 |
| | 3/8 | Double Vee | 5/32 | 120.9 | 35 | -- | -- | 8 |
| Hastelloy C | 3/32 | Square butt | 3/32 | 113.8 | 19.8 | -- | -- | 8 |
| | 3/8 | Double Vee | 5/32 | 115.0 | 24 | -- | -- | 8 |
| Hastelloy R-235 | -- | Ditto | -- | 136.0 | 18.5 | -- | -- | 8 |
| | 0.016 | -- | -- | 117.6 | | 89 | 10 per cent cold worked, welded | 42 |
| | 0.040 | -- | -- | 128.3 | -- | 98 | Solution heat treated,[(b)] welded | 42 |
| | 0.020 | -- | -- | 137.9 | -- | 86 | Solution heat treated,[(c)] aged, welded | 42 |
| | 0.040 | -- | -- | 132.0 | -- | 94 | Solution heat treated, welded, aged | 42 |
| Hastelloy X | 1/8 | Square butt | -- | 110.1 | 26.2 | -- | -- | 8 |
| | 3/8 | Double Vee | -- | 107.6 | 22.4 | -- | -- | 8 |

(a) Flat position.
(b) 1975 F, water quench.
(c) 1500 F, 2 hr, air cool.

Reactor Applications. Gas-shielded arc-welding processes are preferred for many nuclear applications because of the increased joint cleanliness that can be obtained, particularly at the root of the weld, and because of the adaptability of the process to various materials (Ref. 34).

Some nickel-base alloys have excellent resistance to chloride stress-corrosion cracking combined with good corrosion resistance to fuels and coolants that are used in reactor and radiochemical piping. For these reasons Inconel 600 has been used in the primary systems of certain nuclear-power plants. Also, the process is used often, with or without a consumable insert, for making root-pass welds in piping joints. The tungsten-arc process provides sound weld deposits, free from porosity and fissures. In one reactor, the welded joints had to be flawless (Ref. 34). The gas tungsten-arc process was selected for making the welds (in preference to shielded metal-arc welding). The welders who made these critical welds were skilled and capable of the highest possible quality welding. During this work, welding procedures that insured crack-free, porosity-free, full-penetration welds without the use of backing rings were developed. The procedure included the use of a root opening, argon shielding through the torch, helium shielding for the underbead side, and the use of Inconel 600 filler wire.

Filler metal MIL-EN87/RN87 was designed primarily for gas tungsten-arc and gas metal-arc welding of nickel-chromium-iron alloys such as Inconel 600 for nuclear-power-plant applications. This filler metal has produced crack-free and porosity-free welds under conditions of high restraint in plate and in simulated tube-to-tube sheet joints (Ref. 36).

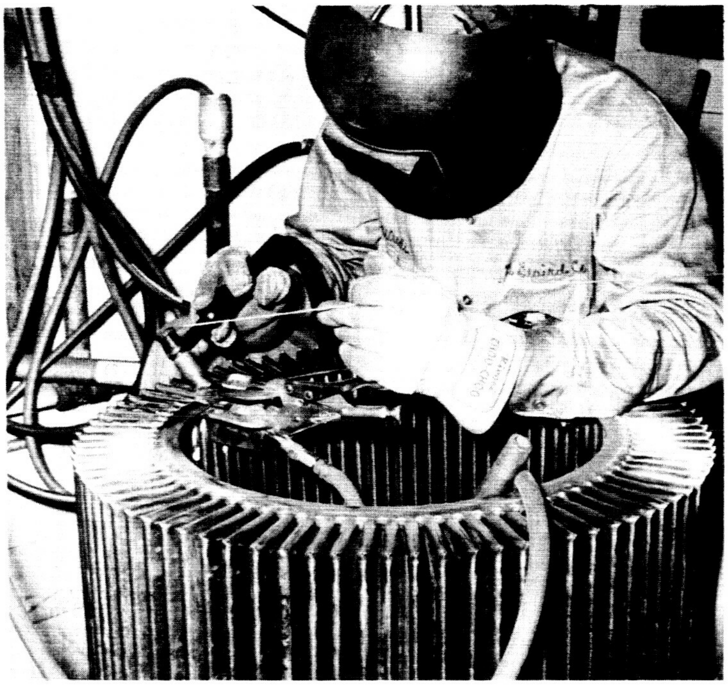
Inconel X also has been used for pressure-vessel applications for operation at high stress levels between 1000 and 1300 F (Ref. 14). Gas tungsten-arc welding was selected on the basis that weld-metal deposits could achieve an ultimate tensile strength of 92 to 93 per cent of the base metal, in addition to other advantages. Much useful information was generated during welding-procedure development. Consistently sound root passes could be made without the addition of filler metal. Inert-gas backing was needed to avoid oxide formation. Modified welding techniques, low welding current, and narrow stringer passes were required to avoid microcracks and fissures in filler passes, and to provide proper root penetration. Dendritic structures, in addition to oxides and microcracks, had a major effect

on rupture life. Cracking problems were not encountered except those associated with weld defects that were present before heat treatment. The heat-treating sequence for weldments also differed from the heat treatment recommended for unwelded material as shown below

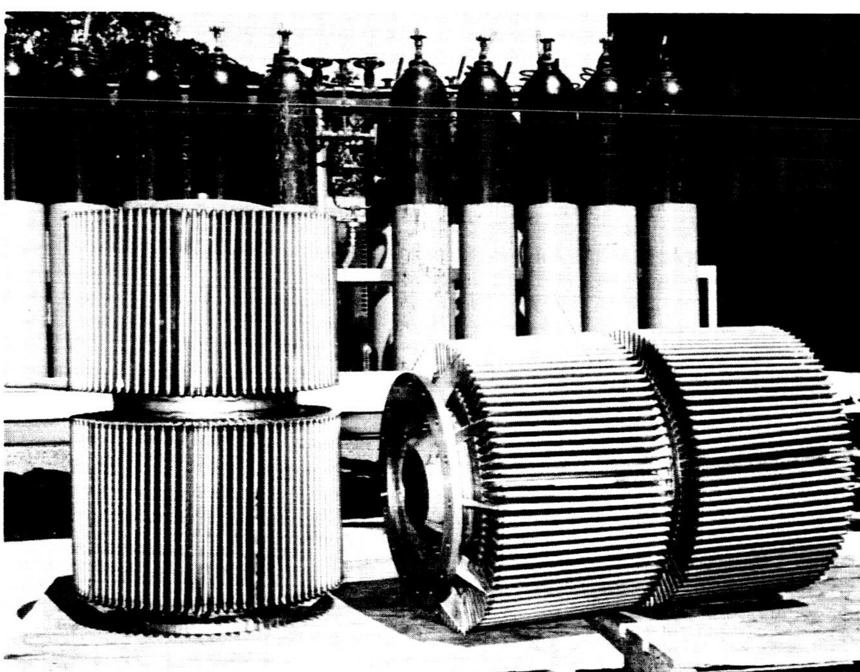
| | For Service Below 1100 F | For Service Above 1100 F |
|---|---|---|
| Initial material condition | 1900 F (mill anneal) | 2100 F (solution anneal) |
| For nonwelded fabrication | 1300 F, 20 hr | 1550 F, 24 hr then 1300 F, 20 hr |
| Fabricated and welded | 1625 F, 4 hr then 1300 F, 20 hr | 1625 F, 4 hr then 1300 F, 20 hr |

Some difficulties have been experienced with microcracking in thin-sheet Inconel X weldments during postweld heat treatment. These cracks are believed to be caused by high residual stress and precipitation-hardening reactions. The effects of various heat treatments on cracking in welded, thin-sheet Inconel X have been studied using circular-patch-type weld-restraint specimens. Eighteen different heat-treating schedules failed to produce microcracks in the weld fusion or heat-treated zones (Ref. 41).

Heat Exchangers. Gas tungsten-arc welding was used for fabrication of a corrugated Monel heat exchanger, Figure 23, for a shipboard seawater-distillation plant (Ref. 43). The most important factor in success was cleanliness. All welding was performed in an air-conditioned room free from normal shop dirt. Initially, 0.050-inch-thick sheet Monel was welded without filler metal. Failures occurred in these welds because of stress corrosion in areas of microporosity resulting from lack of deoxidizers in the Monel and because of lack of penetration. The use of filler metal and a weaving technique combined with underbead shielding eliminated these problems. Figure 23 illustrates the welding of corrugated fins to an end ring and a completed assembly, respectively. Figure 24 illustrates a manual gas-tungsten-arc-welding technique being used for another type of heat exchanger (Ref. 44). The unit shown is a tube-and-shell-type heat exchanger of Inconel 600. Tube-to-header joints like those shown in the figure are welded regularly by fabricators using either manual or automatic techniques.



a. Subassembly



b. Finished Form

FIGURE 23. GAS TUNGSTEN-ARC WELDING FOR FABRICATING A MONEL-CORRUGATED HEAT EXCHANGER (REF. 43)

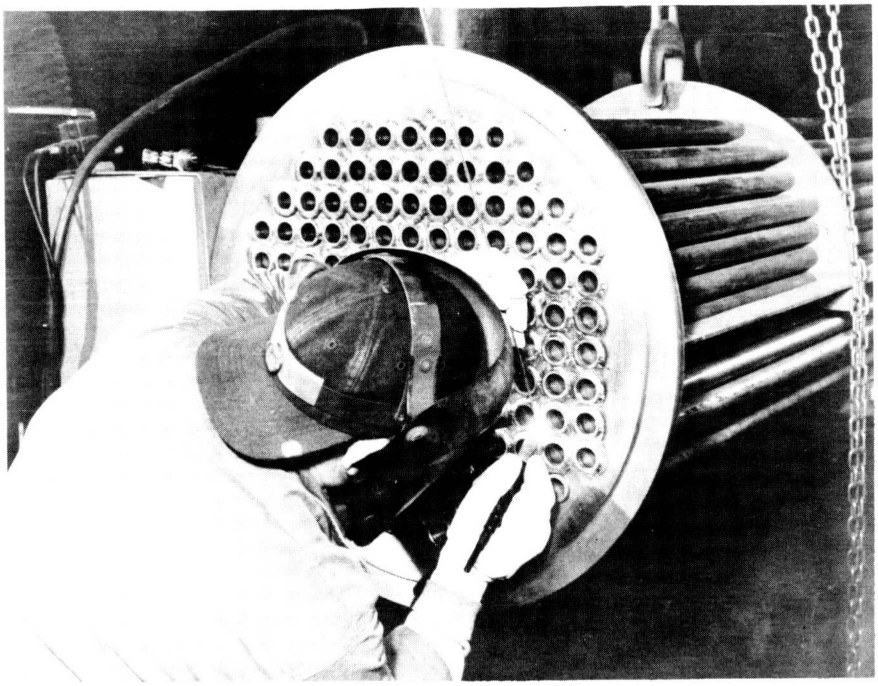


FIGURE 24. MANUAL GAS TUNGSTEN-ARC WELDING OF TUBE-TO-HEADER JOINTS IN INCONEL 600 (REF. 44)

Chemical-Processing Equipment. Welded joints in chemical-processing equipment often must be free from crevices, particularly where corrosion conditions are severe. In addition, the underbead-reinforcement size and geometry must be closely controlled to provide smooth bores. Gas tungsten-arc welding used in conjunction with consumable inserts, proper filler wire, and shielding gas can provide these requirements in nickel pipe (Ref. 45). The consumable insert made from flattened wire and used for making such pipe joints is shown in Figure 25. This insert provided a satisfactory underbead contour for all normal chemical-processing applications. Unless the insert was flattened, the weld did not blend with the pipe bore, and pronounced underbead reinforcement was formed. The consumable insert was made from a nickel-alloy filler wire containing titanium (Nickel Filler Metal 61) to eliminate porosity. When welding for nuclear-power-plant applications, an argon-10 per cent hydrogen mixture for torch shielding, argon backside shielding, and a low-titanium nickel-alloy filler metal (Nickel Filler Metal 41) was used to provide flat, smooth weld beads to produce a smooth bore.

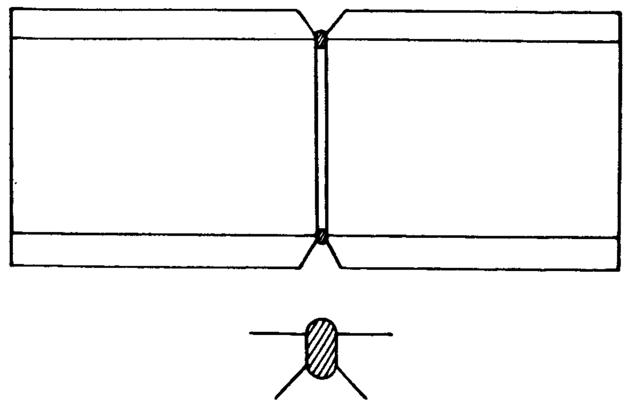


FIGURE 25. CONSUMABLE INSERT FOR WELDING NICKEL PIPE (REF. 45)

Gas Metal-Arc Welding. Gas metal-arc welding is a process that can provide high deposition rates and long arc times as well as ease in welding in the "out of flat position". The process has been used for joining nickel and nickel-base alloys, but has been used to a somewhat lesser degree than gas metal-arc welding for actual production and prototype components. Gas metal-arc welding can be manual, semiautomatic, or fully automatic. It is particularly well suited for the joining of thick sections (greater than about 1/8 inch) where high filler-metal deposition rates are desirable. The process is very economical for this type of work because high weld-finishing rates are obtainable.

In gas metal-arc welding, the heat required to melt the joint edges is supplied by an arc between the filler wire and the work. The filler wire also is called "electrode wire", "consumable electrode", "consumable electrode wire", "filler metal", and "filler wire". The filler wire that replaces the tungsten electrode used in gas tungsten-arc welding is designated as the electrode in gas metal-arc welding as was the tungsten electrode in gas tungsten-arc welding. The gas-metal-arc-welding process is illustrated in Figure 26 (Ref. 38). For welding of nickel and nickel-base alloys the filler wire is usually a matching alloy wire. The arc and surrounding area is kept free of air by a flow of inert gas around the filler wire as is the case in gas tungsten-arc welding. All of the metal added to the weld joint is supplied by the filler wire. This metal is transferred from the filler wire to the workpiece as fine droplets, a metal spray, or by short-circuit transfer. The metal being transferred across the arc may be exposed to much higher temperatures than if it were just being

melted. The combination of very high temperatures and fine-particle sizes represents a set of conditions suitable for contamination. Therefore, in gas metal-arc welding, it is extremely important that the arc area be completely protected from exposure to all harmful gases, i. e., oxygen, nitrogen, hydrogen, water vapor, etc.

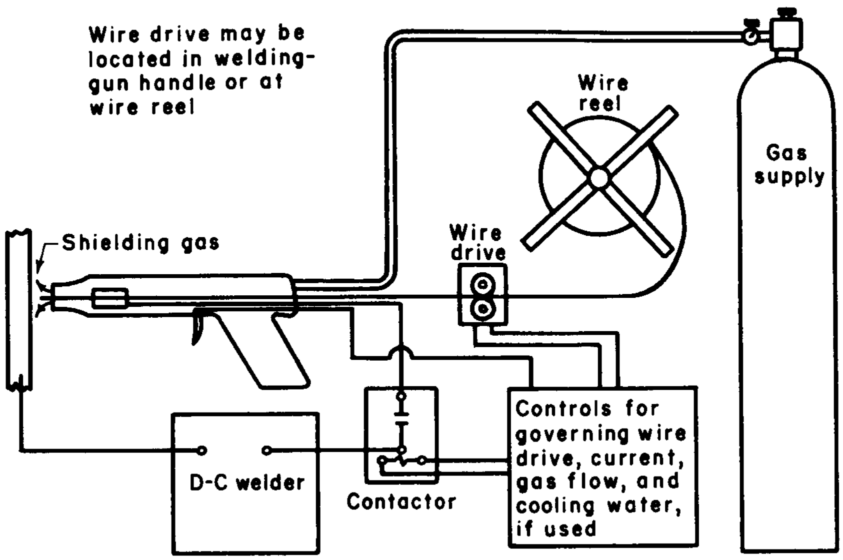



FIGURE 26. GAS-METAL-ARC-WELDING PROCESS (REF. 38)

Gas metal-arc welding of nickel and nickel-base alloys can be performed in all positions. A check should always be made before gas metal-arc welding to insure that adequate gas shielding is obtained, regardless of the welding position. In general, there is more likelihood of there being poor shielding when welding in positions other than the flat position.

Equipment. Conventional gas-metal-arc-welding power supplies, torches, and control systems are used effectively in welding nickel and nickel-base alloys. The nature of gas-metal-arc welding makes this process somewhat more sensitive to changes in welding equipment characteristics than is the case for gas tungsten-arc welding. Various types of constant-speed wire feeders and conventional gas-metal-arc-welding water-cooled torches are used. Most applications of this process have been set up for welding in air.

For in-air welding with the gas metal-arc process, supplemental shielding devices are not generally employed, but they can be used. Trailing shields designed for gas metal-arc welding are usually considerably longer than those used in gas tungsten-arc welding, because larger volumes of material are heated, cool more slowly, and hence require better protection.

Wire-feeding equipment for gas metal-arc welding is important. The most common causes of down time are found in the wire-feed system. For feeding filler wire, a spool of wire is placed on a spindle, threaded through a straightening device and into the grip of wire-feed rolls. From the rolls the wire is pushed through a flexible wire-feed cable, through the gun and into the arc. Hoses and plumbing to supply the gun with shielding gas and cooling water, if used, are included.

The only function of the wire feeder is to move welding filler wire to the arc in such a manner as to provide a sound porosity-free weld deposit. In a correctly designed wire-drive system, the wire is confined laterally so that it can move only in the desired direction. If the drive motor has sufficient power, the wire will move smoothly from spool to gun. Often, there are signals of impending wire-feeding failures. An alert operator becomes aware that the wire speed is varying. Before a complete stoppage occurs, a step-by-step inspection of the equipment should be made to locate and correct the trouble. Precautions that should be taken with wire-feeding apparatus are well known and are reviewed below.

(1) The wire should be snugly wrapped on the spool or coil and should be level wound.

(2) The wire-straightening rolls should be adjusted correctly to remove the "cast" from the wire, and to prevent improper bending.

(3) The unsupported length of wire between the feed rolls and the wire-feed cable should be as short as possible.

(4) The wire should enter at the proper location on the drive rolls.

(5) The drive-roll clamping pressure should be adjusted properly to prevent slippage due to inadequate pressure or to prevent flattening the wire due to excessive pressure.

(6) The wire-feed cable should be clean and free of kinks to insure free movement of the wire through the cable and to prevent wire whip due to a kinked feed cable.

(7) The correct-size wire-feed cable and/or liner for the wire should be used.

(8) Parts showing excess wear should be replaced.

(9) The first and final test for a wire-feed system is the ease of wire movement.

The gas-metal-arc-welding gun or torch is the last link in the wire-feed chain. Its functions are also concerned with electric power and shielding gas. One of its functions is to transfer welding power to the wire, preferably at the exit end of the contact tube. Its other major function is to direct a gas shield over the weld zone so as to exclude the adjacent atmosphere. The gun must be kept in good condition to produce good welds. Bent, worn, or broken parts should be replaced.

The contact tubes are usually made of copper or some special copper alloy. Contact tubes can malfunction due to collection of spatter and excessive wear, or they can melt when the wire burns back as a result of wire-feed failure. Burn backs are generally caused by arcing in the contact tube itself. This mades the wire stick, and then the applied voltage burns the wire back further. Worn contact tubes contribute to burn backs because, as the bore size increases, the transfer of electric power to the wire becomes erratic.

Gas coverage, the second function of the gun, is controlled by its nozzle, which is designed to produce a satisfactory gas-flow pattern. When weld spatter builds up, the shape of the gas pattern may change and, if not corrected soon enough, will cause poor welds. The proper rate of gas flow will normally produce a laminar flow at the nozzle tip. The flow rate may not be critical but too low a rate will not supply enough gas to do the job, and too high a rate will cause turbulence, which brings air into the gas shield and contaminates it. Gas leaks or cooling-water leaks can also cause porosity in welds. Bending, plugging or improper installation of parts should be corrected.

Tooling and Fixtures. Backing for gas metal-arc welding nickel and nickel-base alloys varies among fabricators. Backing bars are used to provide root side shielding to facilitate

control of the weld puddle, heat effects of welding, and underbead-reinforcement geometry. Backing bars also are used to minimize distortion by promoting more rapid solidification and cooling of weld metal.

Copper is the most popular material used for backup bars when manual gas metal-arc welding, although other materials can be used if other conditions are adjusted accordingly.

Welding Conditions. The welding conditions employed in gas metal-arc welding are dependent on two separate groups of factors. First, a suitable combination of current and voltage must be selected that will produce the desired arc characteristics. The arc stability and metal transfer occurring in gas metal-arc welding are very dependent on these electrical variables and the composition of the shielding gas used. With low-current densities, metal transfer is erratic and consists of large metal globules. Large globules often contact the workpiece before they separate from the end of the filler wire. This behavior interrupts the arc due to the short circuit formed by the large globules. Current flow continues, however, until the globule melts sufficiently to separate from the end of the filler wire. When separation occurs, the arc reignites and the transfer process continues as before. Low-current-density gas metal-arc welding has been used for welding nickel. One important advantage is that lower currents and heat-input rates can be used than with spray-type metal transfer. As the current density is increased, arc stability is improved and metal transfer changes to a characteristic spray-type transfer. High-current-density welding conditions are generally preferred in the gas metal-arc welding of most materials.

The second group of factors affecting the welding conditions are the material thickness, joint design, weld tooling, and whether manual or machine welding techniques are being used. The first group of factors affecting welding conditions usually set minimum limits on the usable current and voltage. Variation above these minimums combined with the possible variations introduced by the second group of factors make it possible to produce welds of very similar appearance with many combinations of welding conditions. Table XI lists two combinations that have been used for gas metal-arc welding of nickel and its alloys (Refs. 36, 46).

Properties. Information on properties of gas metal-arc welds in nickel and nickel-base alloys has not been reported extensively. Table XII shows properties for a limited number of alloys (Refs. 8, 46).

TABLE XI. CONDITIONS FOR GAS METAL-ARC WELDING SELECTED NICKEL-BASE ALLOYS

| Base Metal and Thickness, in. | Filler Metal and Wire Diameter, in. | Groove Type | Number of Passes | Welding Speed, ipm | Wire-Feed Speed, ipm | Arc Voltage, volts | Current, Amperes, and Polarity | Shielding Gas and CFH Flow Rate: Torch | Trailing | Backup | Remarks | Reference |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Inconel, 1.0 | MIL-EN87/ RN87, 0.062 | -- | -- | -- | -- | 27 | 280 DCRP | A/— | — | — | Manual | 36 |
| Hastelloy C, 0.250 | Hastelloy Alloy C, 0.031 | 60-deg single V | 2 | 30 | 800 | 36,40 | 230 — | He/50 | A/25 | A/25 | Mechanized | 46 |

TABLE XII. PROPERTIES OF GAS METAL-ARC WELDS IN SELECTED NICKEL-BASE ALLOYS

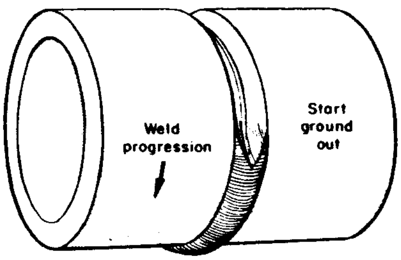
| Base Metal and Thickness, in. | Filler Metal | Test Temperature, F | Transverse Ultimate Tensile Strength, $10^3$ psi | Per Cent Elongation in 2 Inches | Location of Failure | Postweld Treatment | Remarks | Reference |
|---|---|---|---|---|---|---|---|---|
| Hastelloy B, 0.188 | -- | -- | 115.2 | -- | -- | -- | | 8 |
| Hastelloy C, 0.188, | -- | -- | 113.7 | -- | -- | -- | | 8 |
| 0.250 | -- | RT | 116.0/122.5 | 47/49 | Parent Metal | 2225 F, 20 min, air cool, 3 cycles | | 46 |
| 0.250 | -- | 1400 | 75.0/77.0 | 43/47 | Parent Metal | Ditto | | 46 |
| Hastelloy X, 0.125, | -- | -- | 103.7 | -- | -- | -- | | 8 |
| 0.375 | -- | -- | 106.4 | -- | -- | -- | | 8 |

Applications. Gas metal-arc welding is also capable of depositing welding filler metals at high rates. The process has the additional advantage of shielding the parts with inert gas. It has been used successfully for welding a number of nickel-base alloys. Examples of applications are described in the following sections.

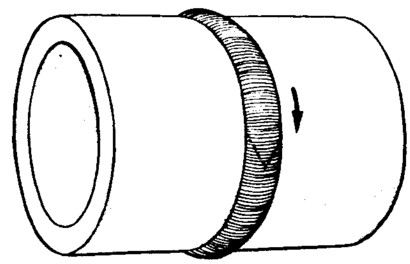
Hastelloy C, Plate and Forging. Hastelloy C has excellent formability, good weldability, and is capable of developing good properties for use at moderately elevated temperatures. Heat treating is relatively simple. The recommended heat-treating temperature, i.e., 2225 F, presents a problem when large parts must be heat treated. Tensile strength, creep, rupture, and thermal-cycling properties of gas metal-arc welds and effects of lower temperature heat treatments (2050 F, 2 hr, air cool) have been reported for gas metal-arc welds (Ref. 45). The welds were made in 0.250-inch-thick plate using 0.031-inch-diameter filler wire. Both materials were Hastelloy C. A single-Vee groove having a 60-degree included angle was used and was filled by making two passes. Torch, trailing, and backup inert-gas shielding was used; 50 cfh helium through the torch, 25 and 20 cfh argon through the trailing shield and backup, respectively. Travel speed was 30 in./min; wire-feed speed was 80 in./min. The first pass was made using 36 arc volts, and the second pass was made using 40 arc volts. The 2050 F heat treatment increased the tensile strength at room temperature and at 1400 F up to 10 per cent, but reduced the yield strength and per cent elongation.

Pipe Welding. Gas metal-arc welding also is used extensively for joining nickel and nickel-base-alloy pipes and tubes for nuclear, marine, cryogenic, and chemical-processing applications. Fabrication in the shop provides the most advantageous conditions where down-hand welding conditions can be arranged. Field fabrication is much more difficult due to the fixed position of the parts being welded. The gas-metal-arc-welding process using short-circuit metal transfer is well suited for such applications. Heat input to the weld zone is low, and the process can deposit large amounts of weld metal rapidly. Some considerations that are normally observed and techniques that are used are discussed in the published literature and summarized below (Ref. 45).

Lack of fusion may be experienced at weld starts due to the low heat input, especially when welding thick materials. This can be overcome by using the design and torch-manipulating techniques shown in Figures 27 and 28 (Ref. 45). Inert-gas shielding such as

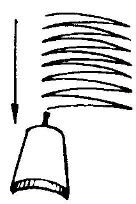



a. First Stage



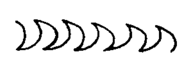
b. Second Stage

FIGURE 27. SUGGESTED STEP-BACK TECHNIQUE FOR OVERCOMING COLD-START DIFFICULTIES WHEN WELDING PIPE WITH THE GAS-METAL-ARC-WELDING PROCESS (REF. 45)



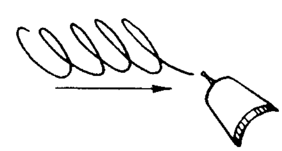
a. Movement of Torch.

Flat and vertical down progression.



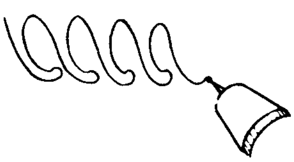
b. Alternative Slower Movement.

Flat position.

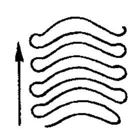


c. Horizontal Vertical Welding.

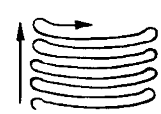
Lower edge leading to provide support of weld metal.



d. Conventional Welding-Torch Head.



e. Vertical Up in Vee.



f. Vertical Up Wide Weave.

FIGURE 28. WELDING-TORCH MANIPULATING TECHNIQUES (REF. 45)

No deliberate pause at toe.

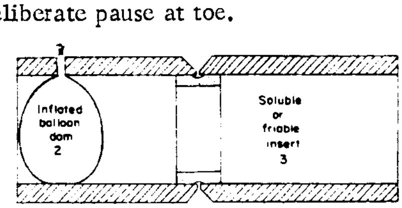



FIGURE 29. A STANDARD METHOD OF APPLYING ARGON TO THE BACK OF A WELD (REF. 45)

argon or helium must be used to exclude air from the weld zones. Both weld-root and weld-face shielding should be used. Shielding the weld face is accomplished with the standard gas-metal-arc-welding torch. Root shielding also must be provided; one interesting technique utilizes an inflatable bag inside the pipe as shown in Figure 29 (Ref. 45).

Arc Spot Welding. Arc spot welding has been developed for use in applications where resistance spot welding cannot be used or as an alternative to the resistance spot-welding process. Arc spot welding can employ either the basic gas-tungsten-arc or gas-metal-arc-welding process. The process can be used to join thickness combinations that are not suitable for resistance spot welding and in joints that are accessible from one side only. Gas tungsten-arc spot welding will probably find major use in the joining of overlapped materials whose total thickness does not exceed 1/4 inch. Gas metal-arc spot welding will be used on thicker sheet up to a maximum of about 2 inches.

The major difference between arc spot welding and either conventional gas tungsten-arc or gas metal-arc welding is that there is no relative lateral movement between the welding torch and the parts being joined. Starting and stopping cycles for the welding process are extremely important in arc spot welding. The total welding time generally is quite short so that it is necessary to automatically program welding parameters to insure a smooth start and stop of the process. The shielding of arc spot welds is somewhat simpler than for conventional gas tungsten-arc or gas metal-arc welds. Simple cylindrical auxiliary shields placed around the welding torch are sufficient to prevent contamination from the top surface of the weld. Shielding of the underside of the joint may not be required unless a full-penetration weld is being made. If welds are full penetration, suitable root shielding also must be provided.

The equipment used for arc spot welding is generally similar to conventional gas-tungsten-arc or gas-metal-arc-welding equipment. However, some means of programming appropriate welding parameters to obtain desired starting and stopping cycles must be available. For welding thicker sheet material, a means of retracting either the welding electrode or the weld contact tube must be a part of the equipment.

Very little information is available concerning the use of arc spot welding for nickel or nickel-base alloys. The process is, however,

used with materials that do not differ significantly from those used in either gas tungsten-arc or gas metal-arc welding. Welding conditions employed in arc spot welding are generally similar to the gas-tungsten-arc or gas-metal-arc-welding conditions used in joining comparable thicknesses of materials. There are indications that the top layer that can be penetrated by gas tungsten-arc welding is limited.

Gas tungsten-arc spot welding is especially adaptable to closing out a joint. The process has been evaluated for use with René 41 (Ref. 32), and possibly has been applied to other metals. Welds were made in two-ply pile-ups of 0.010, 0.020, and 0.040-inch-thick sheets of René 41 sheets. Four major problems were encountered. These were cratering, surface oxidation between sheets, sheet separation, and element segregation in the weld. Surface craters were eliminated by using down-slope current control, and oxidation was reduced by using short weld times. The remaining problems are yet to be investigated.

Submerged-Arc Welding. Submerged-arc welding has been used for joining a limited number of nickel alloys. Only nickel, Monel, Inconel and Hastelloy alloys have been submerged-arc welded (Ref. 8). The lack of suitable filler metals and fluxes and the high-heat-input requirements have limited the usefulness of the process for nickel-base alloys. The process is applicable to a wide range of base-metal thicknesses and it is adaptable to semiautomatic or fully automatic operations. In submerged-arc welding the heat required to melt the filler metal and joint edges is provided by an arc between a metal electrode and the work. The ends of the welding electrode and the weld puddle are covered during welding with a protective submerged-arc-welding flux.

Conventional equipment is used for submerged-arc welding of nickel and nickel-base alloys. Three types of power supplies are used for submerged-arc welding and include variable voltage d-c generators or rectifiers, constant-voltage d-c generators or rectifiers, and a-c transformers. Most submerged-arc-welding installations require high currents at high duty cycles. Thick sections may require welding currents as high as 4000 amperes at 55 volts, while thin sections may be welded at 300 amperes and 20 volts (Ref. 47). Filler metals used with the process are bare rods or wires. Submerged-arc-welding fluxes consist of granulated mineral materials that are made according to chemical specifications and are available in a number of ranges of particle sizes. The flux that is selected for submerged-arc welding depends on the procedure that is used, joint design, and the alloy being welded.

The submerged-arc-welding operation is started by striking an arc on the workpiece beneath a blanket of flux. The arc may be initiated by touch starting, by inserting a pad of metal wool between the end of the welding electrode and the workpiece, or by the use of high-frequency current. Once the arc is initiated, the heat produced melts the surrounding flux. Submerged-arc-welding fluxes generally are electrically conductive when molten. The molten flux is necessary to permit continuous operation of the arc.

Joint designs for submerged-arc butt welding nickel-base alloys are shown in Figure 30 (Refs. 15, 16). The information available on welding conditions for nickel-base alloys is limited. Welding conditions available in the literature for Monel 400 and Inconel 600 are given in Table XIII. Available information on typical mechanical properties of submerged-arc welds is given in Table XIV. Filler wires and fluxes are available for only a limited number of nickel-base alloys – wrought Monel and Inconel 600 (Refs. 15, 16). Submerged-arc welding of other nickel-base alloys probably will be realized only after suitable filler wires, fluxes, and satisfactory procedures are developed.

Electron-Beam Welding. Electron-beam welding also is a useful process for joining nickel and nickel-base alloys. The process is applicable to a wide range of thicknesses from about 0.0015 inch to over 2 inches. One major advantage of the process is that welding is performed in a high-vacuum chamber. Contamination of the weldment from external sources is essentially nonexistent. All electron-beam welding is done using mechanized equipment. Electron-beam welds made with high-power-density-type equipment exhibit a characteristic high depth-to-width ratio for both the weld metal and the heat-affected zone. This characteristic is advantageous from the standpoint of minimizing the distortion that normally accompanies welding. It may also result in welds whose properties are not altered significantly from those of the base material. Investigations also are in progress to develop electron-beam welding in open-air atmospheres (Ref. 48).

In electron-beam welding, the heat required to melt the joint edges is supplied by a focused electron beam generated in an electron gun. This beam is focused and accelerated so that it strikes the joint line parallel to the existing interface. The electron beam can concentrate a large amount of energy in a spot diameter of about 0.010 inch or less (Ref. 49). Energy densities range from about 5,000 to 40,000 kw/in.$^2$, compared with about 100 kw/in.$^2$ for tungsten-arc

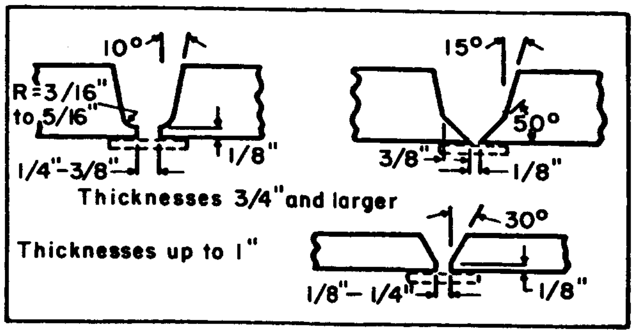



FIGURE 30. TYPICAL BUTT-WELD JOINT DESIGNS FOR SUBMERGED-ARC WELDING F (REF. 15)

TABLE XIII. PROCEDURES FOR SUBMERGED-ARC BUTT WELDING NICKEL-BASE ALLOYS (REFS. 15,16)

| | Monel 400 (Up to 1-3/4 In. Thick) | Inconel 600 (Up to 2 In. Thick) |
|---|---|---|
| Electrode size, in. | 0.062 in. | 0.062 and 0.093 in. |
| Electrode extension, in. | 7/8 to 1 | 7/8 |
| Power source | D-c constant-voltage reverse polarity or straight polarity | D-c constant-voltage reverse polarity or straight polarity |
| Current, amp | 260-280 | 250 (0.062-in. diam)<br>350-400 (3/32-in. diam) |
| Arc voltage | 32-35 | 32-35 |
| Travel speed, ipm | 7-10 | 7 |
| Oscillation | None | None |
| Joint restraint | Full restraint | Full restraint |
| Preheat | None | None |
| Interpass temperature, F | 350 max | 350 max |
| Post-heat treatment | None | None |

TABLE XIV. MECHANICAL PROPERTIES OF SUBMERGED-ARC WELDS IN NICKEL AND NICKEL-BASE ALLOYS (REFS. 15, 16, 17)

| Base Metal | Weld Metal: Ultimate Tensile Strength, psi | Weld Metal: Per Cent Elongation in 2 Inches | Transverse Tension Tests: Ultimate Tensile Strength, psi | Transverse Tension Tests: Location of Failure |
|---|---|---|---|---|
| Nickel | 57,200 | 36.4 | 59,600 | -- |
| Monel | 68,200<br>74,200[a] | 48<br>61[a] | -- | -- |
| Inconel | 95,000[b]<br>-- | 40[b]<br>-- | 84,400[c]<br>83,900[d] | Weld<br>Weld |

(a) Monel Filler Metal 60, submerged-arc-welding flux Incoflux 5.
(b) Inconel Filler Metal 82, submerged-arc-welding flux Incoflux 4.
(c) 1/4 in.
(d) 1/16 in.

welding. Electron-beam welds are usually made without the addition of any filler wire.

Equipment. Any type of electron-beam-welding unit can be used effectively for welding nickel and nickel-base alloys. Units that characteristically produce a low-power-density beam will not produce the high depth-to-width-type weld that can be produced on high-power-density equipment. Historically, electron-beam-welding equipment is classified in two divisions. High-voltage welding is performed in the 75,000 to 150,000-volt range while low-voltage welding is performed in the 15,000 to 30,000-volt range. Normally, the high-voltage equipment produces much narrower heat-affected zones than low-voltage equipment (Ref. 50). A schematic diagram of an electron-beam-welding machine is shown in Figure 31 (Ref. 51). However, acceptable welds can be made with either type of equipment. Special electron-beam units using either clamp-on-type chambers of special electron-gun assemblies designed to allow the electron beam to be projected into the air have not seen much use on nickel alloys. Clamp-on-type chambers may be quite useful in the joining of long lengths of special shapes.

Fixturing is needed to hold the parts in position, but the fixturing need not be as heavy as for other welding methods (Ref. 52). Copper chill bars can be used to restrict the width of the heat-affected zone and to confine and control the fusion-zone geometry (Ref. 29).

Materials. No special material requirements are involved in electron-beam welding. However, because of the very high solidification rates associated with most electron-beam welding, it is imperative that the weld area of the parts to be joined be very clean prior to welding. The high freezing rates associated with electron-beam welding allow very little time for the escape of any gaseous impurities during welding. Thus, it might be anticipated that electron-beam welds could be somewhat more prone to porosity formation than other types of fusion welds. To date, there is very little evidence to either substantiate or refute this supposition.

Welding Conditions. Welding conditions used in electron-beam welding are dependent on material thickness and the type of electron gun being used. For a given thickness of material,

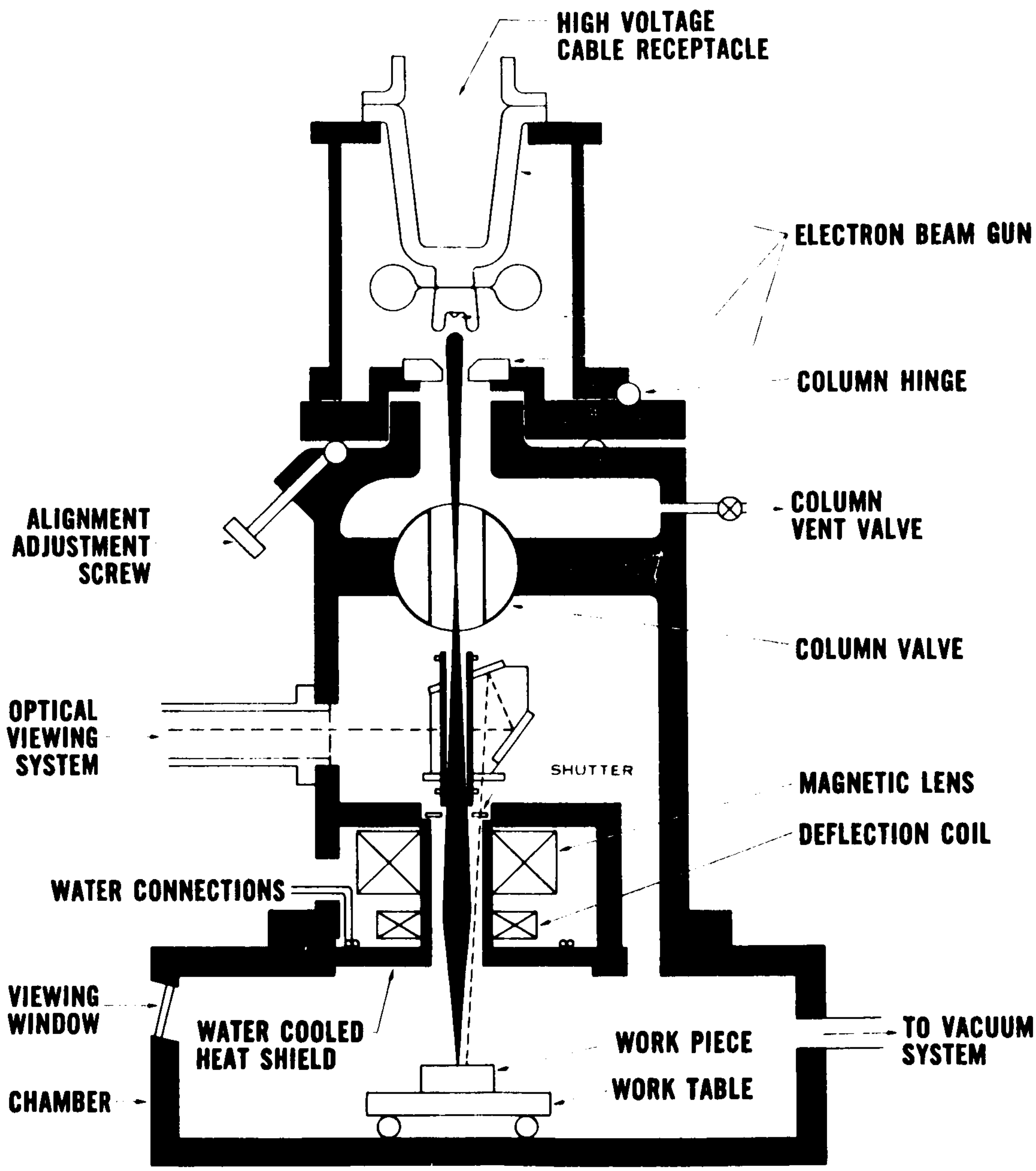



FIGURE 31. ELECTRON-BEAM-WELDING MACHINE (REF. 51)

various combinations of accelerating voltage, beam current, and travel speed are satisfactory. Electrical parameters do not adequately describe the heat-input characteristics of the beam since these characteristics are affected significantly by the focus of the beam. Measurements of beam diameter are difficult to make under production conditions so that the transfer of welding parameters between different equipment units is very difficult. Fortunately, suitable welding parameters can generally be developed with only a very few trials.

In very thick material, the first pass made to completely penetrate the joint sometimes is undercut along both edges of the weld metal. This undercutting can be eliminated by a second weld pass made at somewhat lower energy levels with a slightly defocused beam. However, undercutting has been largely reduced by making minor adjustments in travel rate (Ref. 29). The underside of electron-beam welds also may exhibit an undesirable contour. Some type of metal-removal operation is generally required to produce an acceptable underside contour.

The flat welding position is generally used in electron-beam welding. The welding positions that can be used are limited by the versatility of the available welding equipment. Obtaining good shielding is not a factor affecting the selection of the welding position during electron-beam welding.

Properties. Information on properties of electron-beam welds in nickel-base alloys is not generally available.

Applications. Electron-beam welding has been used for joining several nickel-base alloys. Applications include pressure-vessel spheres, precision assemblies, structural shapes, and other products.

Electron-beam repair welding has proved economical for making repairs on close-tolerance parts that might otherwise have to be scrapped (Ref. 49). Figure 32 shows a modified Tee weldment made by electron-beam welding two pieces of Monel K-500 (Ref. 53). Typical aerospace configurations also have been fabricated experimentally by nonvacuum techniques (Ref. 48). Nonvacuum electron-beam welds in René 41 sheet have been subjected to various heat treatments before and after welding. Welding was performed in 0.010-, 0.187-, and 0.400-inch-thick material with varying degrees

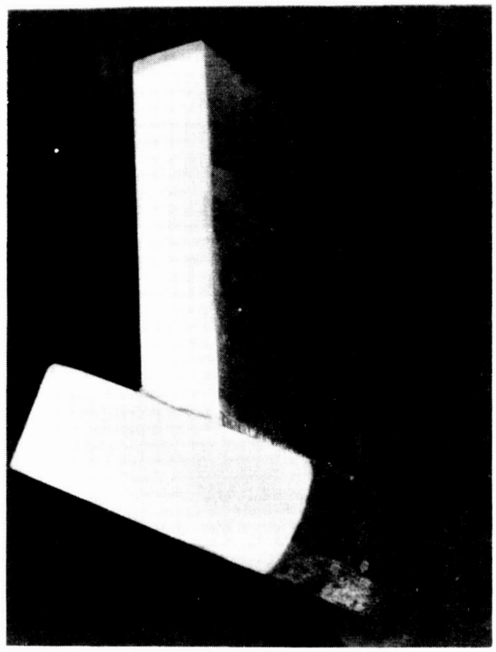


FIGURE 32. MONEL K-500 WELDMENT MADE BY ELECTRON-BEAM WELDING (REF. 53)

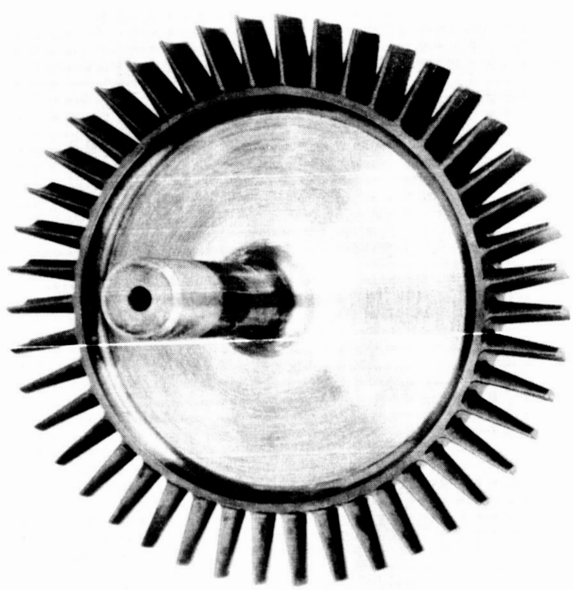


FIGURE 33. BIMETAL TURBINE-WHEEL CONFIGURATION FOR ELECTRON-BEAM WELDING (REF. 48)

of success, depending on variations in welding procedures. The maximum strengths obtained in the various thicknesses are reported later in the section on properties. Porosity seems to be a major problem, but there are indications that some control over porosity can be achieved. Copper backup bars successfully reduced porosity and undercut, particularly in thick sections. Aerospace configurations that have been nonvacuum electron-beam welded included a bimetal turbine wheel consisting of René 41 and Udiment 500 turbine-blade rings welded to an A-286 alloy hub, and René 41 alloy channel sections. The Udimet 500-A286 turbine wheel is shown in Figure 33 after nonvacuum electron-beam welding (Ref. 48).

Plasma Arc Welding. Plasma arc welding is an inert-gas-welding method utilizing a transferred constricted arc. The process is now used as a replacement process for gas tungsten-arc welding in a number of industrial applications. It offers greater welding speeds and better weld quality, and is less sensitive to process variables in certain applications (Ref. 54).

The general characteristics and electrical circuit used for plasma arc welding are shown schematically in Figure 34 (Ref. 54). The arc plasma or orifice gas indicated in Figure 34 is supplied through

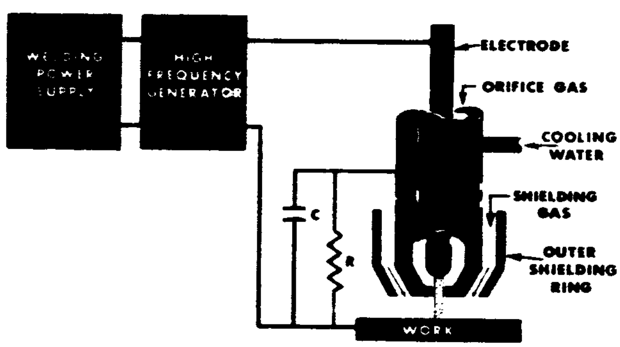



FIGURE 34. PLASMA ARC WELDING (REF. 54)

the torch at a flow rate of 1 to 15 cfh. Suitable gases are argon, argon-hydrogen mixtures, or argon-helium mixtures, depending on the application. The gas flowing through the arc-constricting nozzle protects the electrode from contamination and provides the desired composition in the plasma jet.

Relatively low plasma-gas-flow rates are used to avoid turbulence and undesirable displacement of the molten metal in the weld puddle.

Since the low gas-flow rates are not adequate for shielding the puddle, supplementary shielding gas is provided through an outer gas cup. The type and flow rate of supplemental shielding gas are determined by the welding application. Typical arc and shielding-gas-flow rates are 4 and 35 cfh, respectively.

In plasma-arc welding, the term "keyhole" has been applied to a hole that is produced at the leading edge of the weld puddle where the plasma jet displaces the molten metal, allowing the arc to pass completely through the workpiece. As the weld progresses, surface tension causes the molten metal to flow in behind the keyhole to form the weld bead.

Keyholing can be obtained on most metals in the thickness range of 3/32 to 1/4 in. and is one of the chief differences between the plasma-arc and gas tungsten-arc processes. Presence of the keyhole, which can be observed during welding, gives a positive indication of complete penetration.

Equipment. A mechanized plasma arc-welding torch is shown in Figure 35 (Ref. 54). This torch can be operated with either straight- or reverse-polarity connections at arc currents up to 450 amperes. Water-cooled power cables are connected at the top of the torch to supply power and cooling water to the electrode. Fittings are provided on the lower torch body for the plasma-gas hose, the shielding-gas hose, and cooling water for the nozzle.

The two types of electrodes used in the plasma arc torch are shown in Figure 36 (Ref. 54). The tungsten electrode shown on the left is used for straight-polarity operation and is available in 1/16-, 3/32-, and 1/8-in. diameters, depending on the current to be used. A water-cooled copper electrode, shown on the right in Figure 36, is used for reverse-polarity operation.

Several types of multiport nozzle designs are available for different welding applications. The diameter of the nozzle's central port depends on the welding current and gas-flow rate. The spacing between the side gas ports is influenced by the thickness of the workpiece.

Welding Conditions and Weld Properties. Plasma arc welding has been used in a number of industrial applications for welding Monel, stainless steels, titanium, and zirconium (Refs. 54-56).

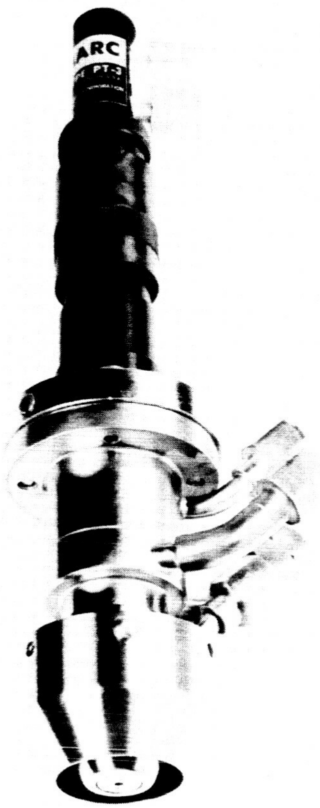


FIGURE 35. MECHANIZED PLASMA ARC-WELDING TORCH (REF. 54)

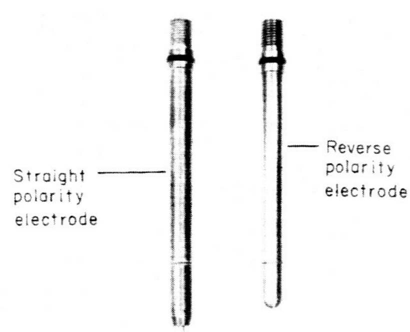



FIGURE 36. TUNGSTEN AND COPPER ELECTRODES FOR STRAIGHT - AND REVERSE - POLARITY OPERATION (REF. 54)

There are no published data, however, for nickel or nickel-base alloys. Conditions determined for joining stainless, however, can be used as starting conditions for welding the same thicknesses of other materials. These starting conditions are reported in Table XV (Ref. 54).

There are no data available in the published literature at this time on properties for plasma arc welds in nickel and nickel-base alloys.

Applications. Plasma arc welding is in use for making circumferential joints in 70-30 copper nickel, Monel, and stainless steel pipe where the pipe can be rolled. Reported advantages of the process compared with gas tungsten-arc welding include simplified joint preparation, higher welding speed, and backing-ring elimination.

Resistance Spot Welding. Resistance spot welding has been used extensively for joining nickel and its alloys in a wide range of thicknesses. The thickness that can be welded in any given application is limited only by the power and force capacity of the available equipment.

In resistance spot welding, all the heat required to accomplish joining is supplied by the passage of an electric current between two opposed electrode tips that contact the surfaces of the parts to be joined. In conventional spot-welding practice, a localized volume of metal at the sheet-to-sheet-interface region melts, then solidifies to form the weld. Techniques can also be used to make welded joints in which no melting is involved; such welds may be called solid-state welds. Joints of this type are very similar in most regards to conventional resistance welds with the exception that no molten metal is formed during the joining process. Even conventional spot welds in many materials contain an area around the molten nugget that is diffusion bonded. The bond in this area may be strong enough to make a significant contribution to the load-carrying ability of the spot weld.

Nickel and nickel-base alloys are spot welded in much the same manner as other metals. In many respects, these alloys are easy to resistance spot weld. The configurations involved in spot welding and the relatively short-time periods used with the process tend to preclude any contamination from the atmosphere. As a result, there appears to be little need to consider auxiliary shielding of nickel during resistance spot welding. The thermal and electrical conductivities, and mechanical properties of nickel and nickel-base alloys vary

TABLE XV. STARTING CONDITIONS FOR PLASMA ARC WELDING NICKEL AND NICKEL-BASE ALLOYS[a] (REF. 54)

| Thickness, in. | Welding Speed, ipm | Arc-Current, amperes DCSP | Arc Voltage, volts | Gas and Flow Rate, cfh Nozzle | Gas and Flow Rate, cfh Shielding |
|---|---|---|---|---|---|
| | | Square Butt Joints | | | |
| 3/32 | 28 | 160 | 31 | 5 A-H[b] | 35 A-H[b] |
| 1/8 | 24 | 145 | 32 | 10 A | 35 A |
| 3/16 | 16 | 165 | 36 | 12 A | 45 A |
| 1/4 | 14 | 240 | 38 | 18 A | 50 A |
| | | Butt Joints in Tubing | | | |
| 0.109 | 36 | 115 | -- | 10 A-H[c] | 30 A-H[c] |
| 0.125 | 36 | 210 | -- | 10 A-H[c] | 40 A-H[c] |
| 0.150 | 36 | 210 | -- | 10 A-H[c] | 45 A-H[c] |
| 0.126 | 15 | 200 | -- | 12 A-H[b] | 45 A-H[b] |
| 0.237 | 14 | 270 | -- | 15 A-H[b] | 45 A-H[b] |

(a) Data for stainless steels: 3/16-in. torch-to-work distance; 1/8-in. setback.
(b) Argon - 7.5 per cent hydrogen.
(c) Argon - 15 per cent hydrogen.

depending on the alloy and its condition. Conditions for spot welding, therefore, are adjusted to account for the material properties as with other materials. For example, electrical resistivity is low for low-carbon nickel and high for Inconel X. The low-resistivity materials require higher current, but usually less pressure. Usually, several combinations of welding variables can produce similar and acceptable results.

Equipment. Nickel and nickel-base alloys have been welded successfully on almost all types of conventional resistance spot-welding equipment. Spot-welding equipment normally provides accurate control over the basic spot-welding parameters: weld current, weld time, and electrode force. Various data indicate that each of these parameters may vary to a certain degree without appreciably reducing weld quality. It is, however, desirable to have enough control over the parameters to obtain reproducible results, once the optimum settings are obtained for a given application. Thin sheet can be welded with most of the 30-kva, 60-cycle, single-phase, rocker-arm-type machines. Because of the higher currents and electrode forces required for thicker sheet and for the harder alloys, the larger press-type machines are more suitable. Upslope controls are used to help prevent expulsion, but downslope and postweld heat controls have not demonstrated any advantages when used in welding these alloys. No significant changes in welding characteristics or static weld properties have been reported that can be attributed to the use of any specific type of resistance-welding equipment, but there may be a preference by some fabricators for three-phase equipment.

Electrode alloys generally recommended for spot welding nickel and its alloys include RWMA Classes 2 and 3 and a molybdenum-tipped electrode. In conventional practice, internally cooled electrodes are recommended to improve tip life. For small parts, the electrodes often are not water cooled. Both flat face and spherical radius tip geometries are used. With the soft nickel or nickel alloys a low bevel angle will reduce sticking to a minimum. Full-domed electrodes should not be used for high-nickel-base alloys because these alloys resist indentation and prevent proper forging. The amount of indentation and weld strength can vary from weld to weld because of slight variations in sheet temper.

When designing sheet-metal assemblies for resistance spot welding, the factors that should be considered are the same as for other materials. These factors include:

(1) Joint Overlap — A sufficient amount of overlap should be provided to contain the weld. Suggested minimum joint-overlap values range from 0.250-inch for 0.005-inch-thick sheets to 1.875 inch for 0.125-inch-thick sheets.

(2) Accessibility — Spot welds should be placed in locations that are accessible with the equipment to be used.

(3) Flatness — Forging pressure will be inadequate if part of it is used to form the parts to provide proper contact.

(4) Weld Spacing — Insufficient spot weld spacing causes reduced current at the desired location due to shunting to some current through previously made welds. Recommended minimum spot-weld-spacing values for annealed nickel range from 0.50 to 2.25 inches for 0.005 and 0.125-inch-thick sheets, respectively.

Welding Conditions. Resistance spot-welding conditions are primarily controlled by the total thickness of the assembly being welded, and to a rather large degree, by the welding machine being used. Similar welding conditions may be perfectly suitable for making welds in the same total thickness where the number of layers differs significantly. However, for any given thickness or total pileup, various combinations of welding current, time, and applied force may produce similar welds. Other variables such as electrode size and shape are important in controlling such characteristics as metal expulsion, sheet indentation, and sheet separation. The use of slope controls to obtain preheat, postheat, and additional weld forging is used for some high-strength alloys such as René 41 (Refs. 57, 58).

Nickel and nickel-base alloys that have properties similar to steel behave in welding like steel. The high-nickel alloys generally are harder and stronger than low-carbon steel, particularly at elevated temperatures; greater pressures are therefore required during spot welding. The time of current flow should be as short as possible. For very thin sheet and fine wires, weld time usually is less than 2 cycles and often is less than 1 cycle (60-cycle current). Current is set at a value that is somewhat above the value that produces a weak or just "stuck" weld, but below values that produce expulsion. Upslope controls that gradually increase current to final values are used to help reduce expulsion.

Table XVI lists spot-welding conditions used for nickel and some selected nickel-base alloys (Refs. 8, 31, 59, 60).

Properties. The quality of spot welds is determined by several testing methods. In addition to cross tension and tension-shear-strength requirements, many specifications, such as company specifications and the military specification MIL-W-6858B (Ref. 61), place certain restrictions on weld penetration, sheet separation, electrode indentation, and weld diameter (Ref. 57).

Many properties and characteristics of resistance spot welds in nickel and nickel-base alloys have been determined. The properties that usually are determined are reported in Table XVI. Additional information is available in the published welding literature. In many instances, complex testing procedures are required to determine the behavior of spot welds under special conditions. The fatigue properties of spot welds are low, but this behavior is more characteristic of the joint type than of the material.

Applications. Resistance spot welding has been used for many years for joining the familiar nickel and nickel-base alloys. Spot welding is an important joining method for these alloys, for the newer nickel-base alloys, and for applications to new products. The process is important in the field of electronic components and aerospace components in addition to its many past uses. Spot welding is used principally for joining sheet metals in thicknesses ranging from about 0.001 to 0.250 inch.

Extensive information is available in the published literature concerning spot welding of the nickel-base alloys. Much recent effort has been placed on spot-welding developments for some high-strength alloys. Spot welding of René 41 alloy, for example, was investigated in conjunction with the X-20 airplane program. Special techniques were developed for spot welding this alloy (Ref. 57). René 41 required preheat and rigid control of heat buildup and molten nugget formation during welding. In addition, forging pressure was needed during a postheat time to prevent weld cracking. A diffusion-bonded ring was formed with these schedules around the molten weld metal and helped minimize expulsion of molten weld metal. The techniques also helped eliminate weld-metal-shrinkage cracks. The effects of weld quality on static mechanical properties, fatigue properties, and vibration testing at room and elevated temperatures were determined. Thickness combinations greater than 2.5 to 1 were

TABLE XVI. RESISTANCE-SPOT-WELDING CONDITIONS AND PROPERTIES FOR NICKEL AND SELECTED NICKEL-BASE ALLOYS

| Thickness, in. | Dome Diameter, in. | Electrode Force, lb | Weld Time, cycles | Current Welding, amperes | Fused Zone or Weld Diameter, in. | Average Shear Strength, lb | Tension/Shear Ratio, per cent | Reference |
|---|---|---|---|---|---|---|---|---|
| | | | | Annealed Nickel Sheet | | | | |
| 0.005/0.005 | 5/32 | 100 | 3 | 7,100 | 0.10 | 40 | -- | 59 |
| | | | | | | | | 59 |
| 0.031/0.031 | 3/16 | 900 | 4 | 15,400 | 0.18 | 950 | -- | 59 |
| | | | | | | | | 59 |
| 0.125/0.125 | 3/8 | 3300 | 20 | 31,000 | 0.37 | 7000 | -- | 59 |
| | | | | TD Nickel | | | | |
| 0.050 | | (Solid-state, back brazed) | | | | 1585/1595 | -- | 31 |
| 0.050 | | (Fused nugget, back brazed) | | | | 1580/1590 | -- | 31 |
| 0 | | | | Annealed Monel Sheet | | | | |
| 0.005/0.005 | 5/32 | 220 | 2 | 5,000 | 0.10 | 70 | -- | 59 |
| 0.031/0.031 | 3/32 | 700 | 12 | 10,000 | 0.17 | 1056 | -- | 59 |
| 0.125/0.125 | 1/2 | 5000 | 30 | 30,000 | 0.47 | 7300 | -- | 59 |
| | | | | Annealed Inconel Sheet | | | | |
| 0.005/0.005 | 5/32 | 300 | 2 | 7,000 | 0.11 | 90 | -- | 59 |
| 0.031/0.031 | 3/16 | 700 | 12 | 6,700 | 0.18 | 1150 | -- | 59 |
| 0.125/0.125 | 7/16 | 5270 | 30 | 20,100 | 0.44 | 8000 | -- | 59 |
| | | | | Hastelloy R-235 | | | | |
| 0.030/0.030 | 7/32 | 1200/2700[b] | 8/2/2[b] | 20,000 | 0.156 | 1255 | 64.6 | 8 |
| 0.063/0.063 | 5/16 | 2000/4000[a] | 10/2/8[b] | 21,500 | 0.250 | 3268 | 80 | 8 |
| 0.094/0.094 | 3/8 | 4000/8000 | 10/2/4[b] | 28,600 | 0.344 | 5780 | 67.5 | 8 |
| | | | | Hastelloy X | | | | |
| 0.030/0.030 | 7/32 | 900/2500[a] | 8/2/2[b] | 18,900 | 0.156 | 1379 | 63.2 | 8 |
| 0.063/0.063 | 5/16 | 2500/4000[a] | 10/2/10[b] | 21,700 | 0.266 | 3286 | 59.4 | 8 |
| 0.094/0.094 | 3/8 | 4400/7500[a] | 9/2/4[b] | 30,500 | 0.344 | 4816 | 89.0 | 8 |
| | | | | Inconel X | | | | |
| 0.010/0.010 | 5/32 | 300 | 2 | 730 | 0.11 | 320/460[c] | 81.4/39.2[c] | 60 |
| 0.031/0.031 | 7/32 | 1750 | 8 | 9,900 | 0.17 | 1400/1800[c] | 71.5/37.7[c] | 60 |
| 0.062/0.062 | 5/16 | 4400 | 14 | 16,350 | 0.29 | 4300/5600[c] | 79.1/42.8[c] | 60 |

(a) Top value – welding force, bottom value – forging force.
(b) Weld time/cool time/number of pulses.
(c) Top value – as welded; bottom value – after aging at 1300 F, 4 hr.

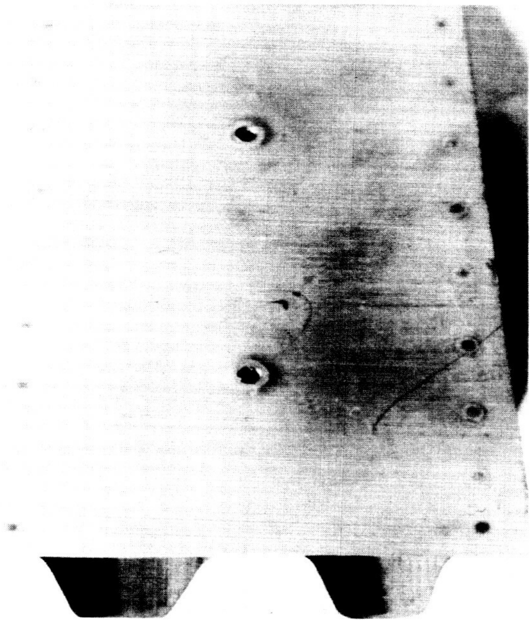
difficult to weld by conventional techniques because of insufficient penetration into the outer sheet (Ref. 58). The use of metal shims permitted joining unequal thicknesses up to 8 to 1 successfully. Past experience has shown, however, that resistance welding of alloys like René 41 and Hastelloy X can be performed with conventional equipment (Ref. 32). In spot welding these alloys oscillographic equipment should be used to insure that the machine is set up and operating properly. Metal fitup is extremely important. If any portion of the electrode force is used to produce metal contact, weld properties will be reduced. Lack of complete cleanliness also results in a deterioration of weld properties.

TD nickel has been resistance spot welded using both solid-state and fusion techniques (Ref. 31). This alloy has very desirable properties for aerospace applications. The properties of spot welds for some applications of TD nickel have been cause for concern, partly because of the unfavorable stress pattern around the weld. Back-brazing techniques have been successful in alleviating this condition in prototype jet-engine components when the resistance welds are subject to fatigue. This technique appears to offer promise for making usable joints with TD nickel.

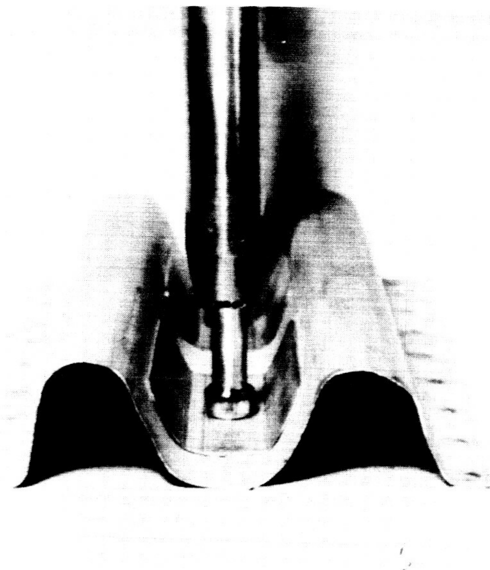
Spot-welding applications for nickel and nickel-base alloys are illustrated in Figures 37, 38, and 39.

Roll Resistance Spot Welding. Roll resistance spot welding is similar in most respects to standard spot welding. The major difference between the two processes is that in roll resistance spot welding, wheel-shaped electrodes are used instead of the cylindrical-type electrode used in conventional spot welding. The use of the wheel electrodes provides a convenient means of indexing the parts between each individual spot weld. Rotation of the wheels is intermittent with the wheel electrodes being in a fixed position during the actual welding cycle. Electrode wear is more uniformly distributed with a wheel-type electrode than it is with a conventional cylindrical electrode, thus it is possible to make many more welds without dressing of the electrodes when using roll spot welding. However, there is somewhat less flexibility with roll-spot-welding techniques than with conventional spot welding.

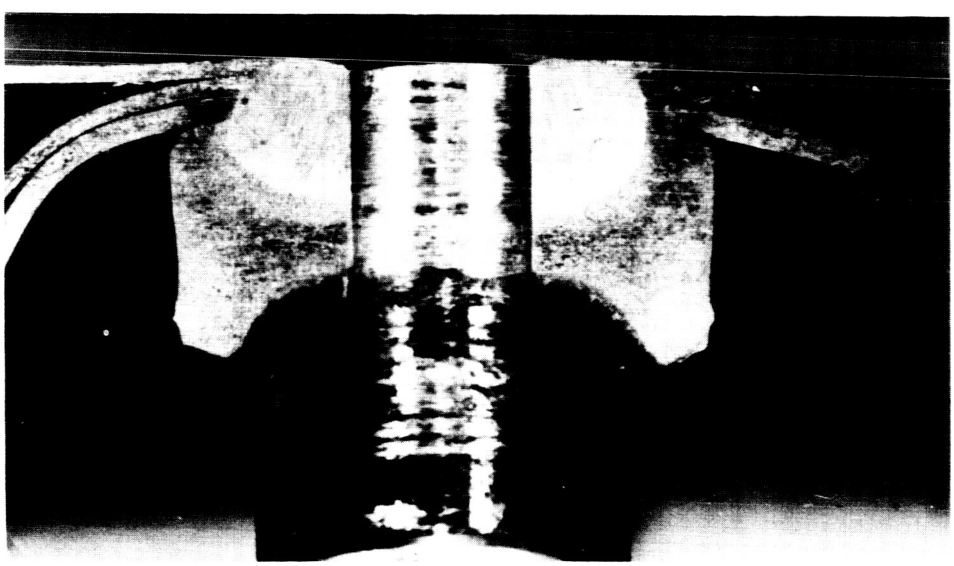
Equipment for roll spot welding differs from conventional spot-welding equipment primarily in that provision must be made to accommodate the wheel-shaped electrodes. Also, a suitable drive



a. Top View of Panel



b. Bottom View of Panel Ready for Welding



c. Cross Section of Spot-Welded Fitting

FIGURE 37. SPOT-WELDED M-252 PORT-FITTING ATTACHMENT TO A THREE-PLY PILEUP OF RENÉ 41 (REF. 58)

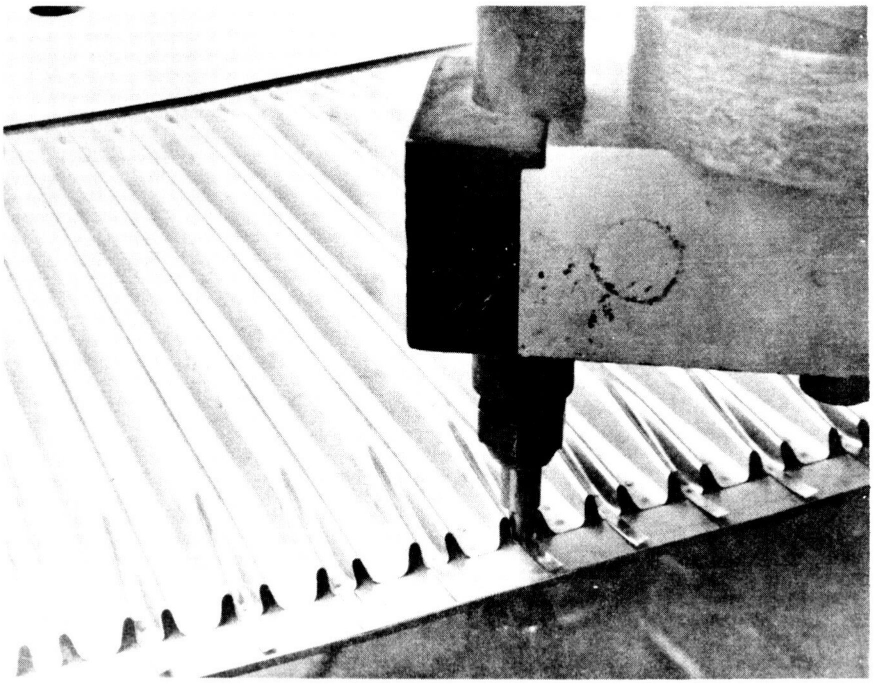


FIGURE 38. SPOT WELDING CREASED-EDGE CORRUGATION TO SKIN AND DOUBLER (REF. 32)

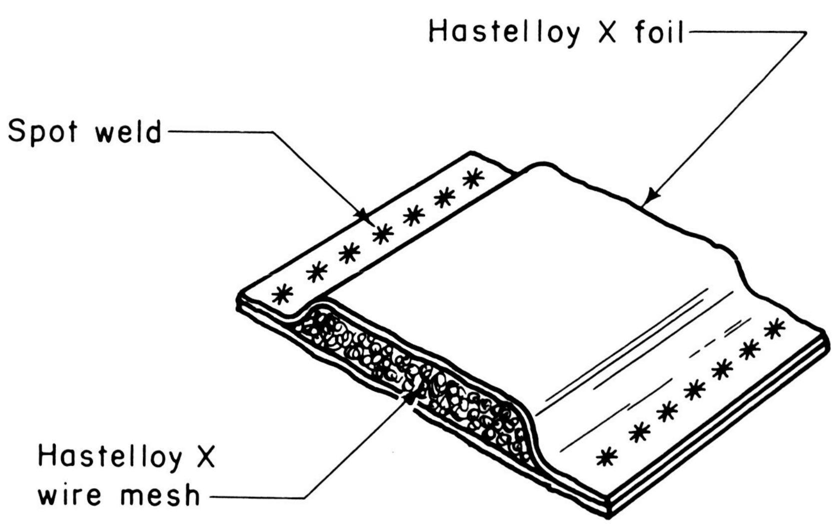



FIGURE 39. SPOT-WELDED WINDOW-SEAL ASSEMBLY FOR SUPERSONIC AIRCRAFT (REF. 57)

and indexing mechanism must be provided. Usually, however, roll resistance spot welding is performed with resistance-seam-welding machines.

Roll-spot-welding conditions have not been found in the literature. It is expected that these conditions would be very similar to conventional spot-welding conditions.

Resistance Seam Welding. Seam welding also is similar to spot and roll spot welding. The principal advantage of seam welding is that it can be used to produce leaktight joints. The principal disadvantage is that there is much more distortion with seam welding than with other types of resistance welding.

In seam welding, wheel-type electrodes instead of spot-welding electrodes are used. Individual overlapping spots are created by coordinating the welding current time and wheel rotation. Seam welds can be made with conventional spot-welding techniques. However, it is much more common to use commercially-available equipment designed specifically for seam welding. In seam welding, the wheels usually can be rotated continually or intermittently. The use of continuous seam welding imposes additional limitations on the weld-cycle variations that can be used. For example, a forge-pressure cycle is not possible during continuous seam welding because of the continuous rotation of the electrodes. Forging pressure can be used with intermittent motion.

Selected data on seam-welding conditions and characteristics of seam-welded joints are given in Table XVII. Additional information on mechanical properties of seam welds in nickel-base alloys is available in published literature (Refs. 8, 17, 57-61). The high-strength alloys such as Hastelloy R-235 and Inconel X usually are welded using forging force and intermittent drive. When the completed weldment is intended for applications requiring leaktight seams, suitable pressure or leak tests are used. In addition, many of the tests applicable to spot welds also are applicable to seam welds.

Applications. Seam welding is used for welding sheet metals usually for applications requiring gastight or leaktight seams. Nickel and many of the nickel-base alloys have been resistance seam welded but, unfortunately, only limited information is available in the published literature. Recommended seam-welding schedules for selected thicknesses of Monel and Inconel alloys, X-750 and 722

TABLE XVII. RESISTANCE-SEAM-WELDING CONDITIONS FOR SELECTED NICKEL-BASE ALLOYS (REF. 8)

| Thickness, in. | Wheel Face Width, in. | Wheel Radius, in. | Electrode Force, lb | Timing On, cycles | Timing Off, cycles | Weld Spacing, Welds per in. | Wheel Speed, in. /min | Weld Current, amperes | Width of Fused Zone, in. | Weld Overlap, per cent |
|---|---|---|---|---|---|---|---|---|---|---|
| **Monel 400** | | | | | | | | | | |
| 0.031/0.031 | 3/16 | 6 | 700 | 4 | 12 | 12 | 19 | 10,000 | 0.15 | 20 |
| 0.062/0.062 | 3/8 | 6 | 2500 | 8 | 12 | 9 | 20 | 19,000 | 0.17 | 10 |
| **Inconel 722** | | | | | | | | | | |
| 0.031/0.031 | 3/16 | 3 | 2300 | 4 | 8 | 10 | 30 | 9,700 | 0.17 | 20 |
| 0.062/0.062 | 1/4 | 6 | 4000(a) | 8 | 16 | 12 | 12.5 | 14,400 | 0.24 | 10 |
| **Inconel X-750** | | | | | | | | | | |
| 0.031/0.031 | 3/16 | 3 | 2300 | 4 | 8 | 10 | 30 | 8,500 | 0.17 | -- |
| 0.062/0.062 | 3/16 | 6 | 4000(a) | 8 | 16 | 12 | 12.5 | 10,300 | 0.18 | -- |

(a) Not optimum but satisfactory where sufficient force is not available.

were given in Table XVII (Ref. 8). Most of the available published literature contains information pertaining to the development of seam-welding schedules for particular nickel-base alloys (Refs. 57-59, 62). It seems that suitable seam-welding schedules can be developed when needed for nickel-base alloys.

Distortion found in seam-welded thin-sheet assemblies can be minimized or eliminated using special tooling or techniques. For welding Inconel X-750 distortion can be minimized by heat treating before welding. Reaging after welding provides improved joint properties (Ref. 62).

Flash Welding. Flash welding is used extensively for joining nickel and nickel-base alloys. Typical products include Monel pickling chains and hot-water tanks, and Inconel rings for jet engines.

In two respects, flash welding is better adapted to the high-strength, heat-treatable alloys than are arc, spot, or seam welding. First, molten metal is not retained in the joint, so cast structures that might be preferentially corroded are not present. Second, the hot metal in the joint is upset, and this upsetting operation may improve the ductility of the heat-affected zone.

Flash welding has several important advantages. Weight saving can be realized because there is no need for overlapping bolting, riveting, or welding flanges. Extruded shapes can be flash welded and, with suitable designs, machining costs can be reduced.

Equipment. Equipment for flash welding is considerably different from equipment used for spot or seam welding. For welding, the parts are held firmly in two copper-alloy dies. One or both of these dies are movable. Current from a welding transformer passes through the dies and into the work. The parts initially may or may not be separated but are advanced toward each other. At the first contact of the parts, the current causes melting of the metal and violent expulsion. This behavior continues until the base metal is heated to welding temperature. Then, the parts are forged together to complete the weld. Welding current usually is shut off at the time forging takes place.

The machine capacity required to weld nickel and nickel alloys does not differ greatly from that required for steel. This is especially true for transformer capacity. The upset-pressure

capacity for making flash welds in nickel-base alloys is higher than that required for steel. Figures 40 and 41 show the transformer and upset capacity required for welds of different cross-sectional areas in Inconel (Ref. 63). Also of importance is the fact that transformer-capacity requirements vary from one machine to another, depending upon the coupling between the parts and transformer.

Joint Design and Joint Preparation. Joint designs for flash welds also are similar to those used for other metals. Flat, sheared, or saw-cut edges and pinch-cut rod or wire ends are satisfactory for welding. For thicker sections, the edges are sometimes beveled slightly. The overall shortening of the parts due to metal lost during welding should be taken into account so the finished parts will be the proper length. Figure 42 shows the metal allowances used in making flash welds in several materials including Inconel (Ref. 63). The allowances include the metal lost in the flashing and upsetting operations.

The flash-welding conditions that are of greatest importance are flashing current, speed and time, and upset pressure and distance. With proper control of these variables, molten metal, which may be contaminated, is not retained in the joint, and the metal at the joint interface is at the proper temperature for welding.

Generally, high flashing speeds and short flashing times are used when it is desirable to minimize weld contamination. Also, the use of a parabolic flashing curve is more desirable than the use of a linear flashing curve because maximum joint efficiency can be obtained with a minimum of metal loss.

Flash-welding variables vary from machine to machine and application to application. Table XVIII illustrates welding conditions for several nickel-base alloys (Ref. 8). Welding current is not given, but welding current and arc voltage depend on the transformer tap that is used.

Properties of Flash Welds. Flash welds that have mechanical properties approaching those of the base metals are being regularly produced in conventional machines. Joint efficiencies of 95 per cent or better are common for flash welds.

The static-tension-test properties of flash-welded joints are summarized in Table XVIII (Ref. 59). The static properties of flash-

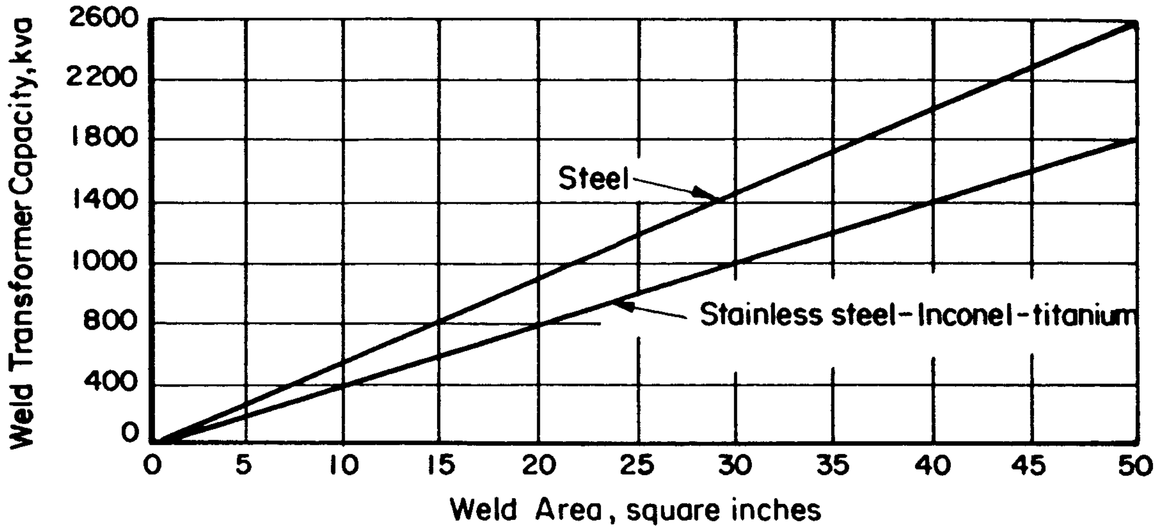



FIGURE 40. TRANSFORMER CAPACITY VERSUS WELD AREA (REF. 63)

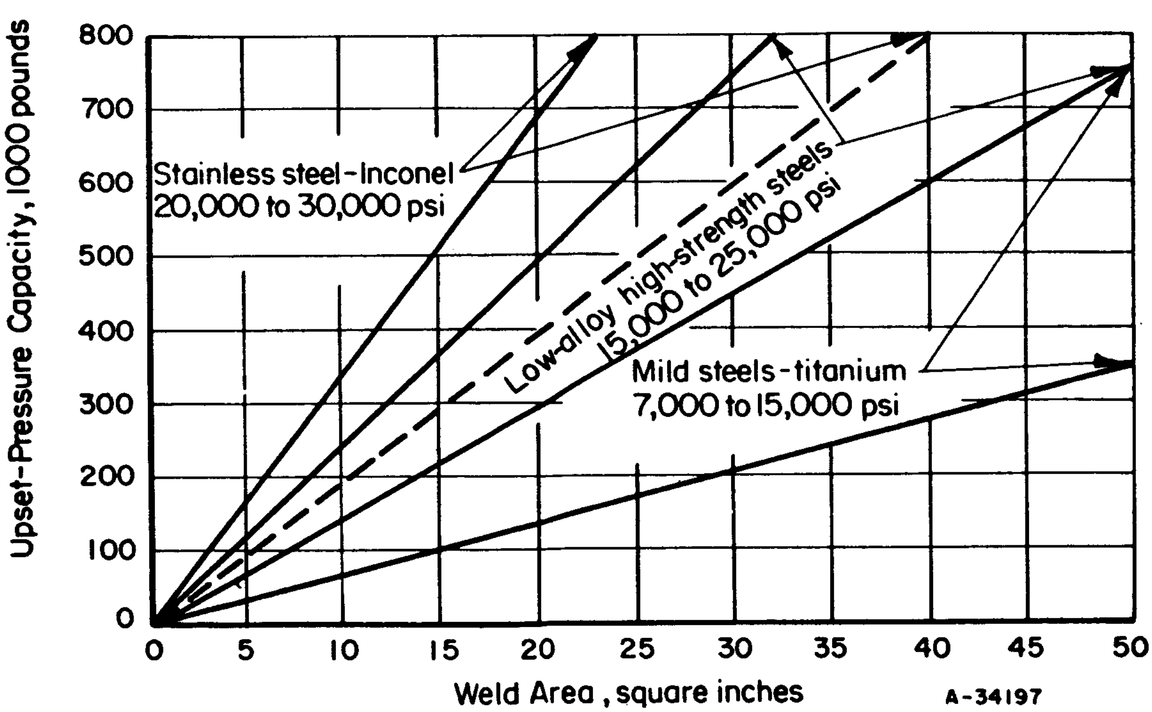



FIGURE 41. MAXIMUM MACHINE UPSET-PRESSURE REQUIREMENTS VERSUS WELD AREA (REF. 63)

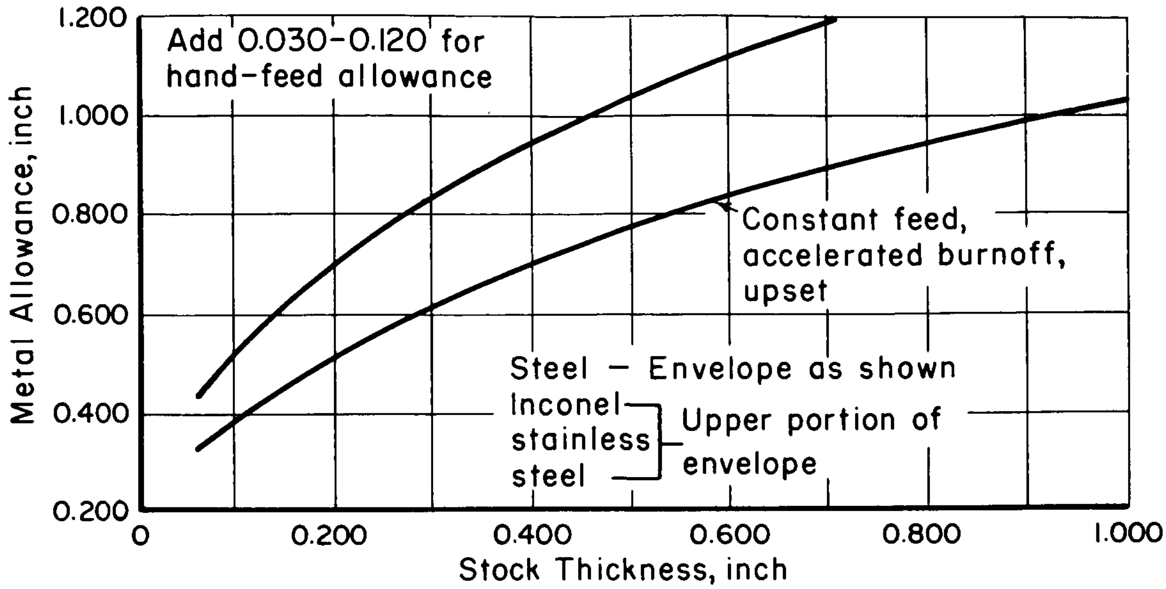



FIGURE 42. TOTAL METAL ALLOWANCE VERSUS STOCK THICKNESS (REF. 63)

TABLE XVIII. WELDING CONDITIONS AND PROPERTIES FOR FLASH WELDS IN NICKEL AND SOME NICKEL-BASE ALLOYS

| Material | Rod Diameter, in. | End Preparation[a] | Flashing Distance, in. | Flashing Time, sec | Duration During Upset, cycles | Current Upset Distance, in. | Watt Hr/Weld | Weld Strength, psi | Rod Strength, psi | Reference |
|---|---|---|---|---|---|---|---|---|---|---|
| Nickel | 1/4 | Pointed | 0.442 | 2.5 | 1-1/2 | 0.125 | 2.15 | 58,000 | 65,100 | 59 |
| Nickel | 3/8 | Pointed | 0.442 | 2.5 | 2-1/2 | 0.145 | 4.87 | 65,600 | 66,500 | 59 |
| Monel | 1/4 | Pointed | 0.442 | 2.5 | 1-1/2 | 0.125 | 1.93 | 68,500 | 70,500 | 59 |
| Monel | 3/8 | Pointed | 0.442 | 2.5 | 2-1/2 | 0.145 | 5.55 | 80,300 | 84,700 | 59 |
| "K" Monel | 1/4 | Pointed | 0.442 | 2.5 | 1-1/2 | 0.125 | 2.02 | 93,900 | 100,000 | 59 |
| "K" Monel | 3/8 | Pointed | 0.442 | 2.5 | 2-1/2 | 0.145 | 4.79 | 98,800 | 99,000 | 59 |
| Inconel | 1/4 | Pointed | 0.442 | 2.5 | 1-1/2 | 0.125 | 2.15 | 101,200 | 109,800 | 59 |
| Inconel | 3/8 | Pointed | 0.442 | 2.5 | 2-1/2 | 0.145 | 5.19 | 102,000 | 106,000 | 59 |
| TD nickel | 0.050[b] | -- | -- | -- | -- | -- | -- | 4,100[c] | -- | 31 |
| TD nickel | 0.125[b] | -- | -- | -- | -- | -- | -- | 63,800 | -- | 64 |
| TD nickel | 0.125[b] | -- | -- | -- | -- | -- | -- | 8100/9060 | -- | 64 |

(a) 110-degree included angle.
(b) Sheet thickness.
(c) At 2000 F.

welded joints in nickel and nickel-base alloys are good. Most tension specimens fail away from the weld centerline with strengths that are almost equal to or exceed those of the base metals.

Applications. Flash welding has been used for joining nearly all of the nickel-base alloys in a variety of forms and shapes (Refs. 59, 65). It is used for butt welding sheet, strip, rod, and extruded sections. The process also is used for joining rings such as jet-engine rings, wheel rims, and chain links. Applications of the process for joining some of the nickel-base alloys are described below.

Flash welding is used extensively for fabricating rings and wheels. A typical jet-engine ring fabricated by flash welding is illustrated in Figure 43. These rings are fabricated by ring rolling of extruded sections and flash welding.

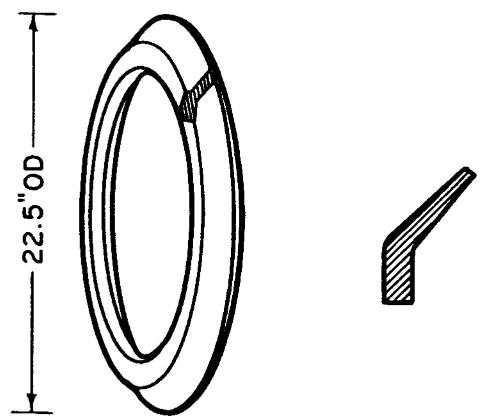



FIGURE 43. ILLUSTRATION OF A FLASH-WELDED L-605 JET-ENGINE RING (REF. 65).

TD-nickel has been flash welded experimentally to develop information on flash-weld performance at high temperatures (Ref. 31). Welding conditions were developed that produced good welds that had 100 per cent joint efficiency. However, joint efficiency in the proposed operating temperature range is only 30 to 40 per cent because of loss of thoria dispersion in the weld zone and reorientation of grains in the heat-affected zone. Agglomeration of thoria and delamination in the weld area also cause problems.

## SOLID-STATE WELDING

In solid-state welding, joints are formed with all components of the joint maintained as solids. Welds can be made under these conditions if two metallic surfaces, which have been prepared properly, are brought together under an applied pressure at a suitable temperature for a sufficient length of time. Deformation and diffusion are important mechanisms of solid-state welding. It is convenient to subdivide this type of welding on the basis of whether deformation or diffusion is the predominant mechanism contributing to weld formation. Both mechanisms probably always operate to some extent during the formation of a solid-state weld, but there are significant differences in the extent to which these two mechanisms control a given welding process. Deformation may be limited to very small surface areas during welding that is controlled primarily by diffusion mechanisms. When considerable deformation is used during the welding operation, diffusion can be quite limited. Both deformation and diffusion welding have been applied successfully to a limited number of nickel alloys.

The term "solid state welding" as used in this report is intended to cover all joining processes in which either diffusion or deformation plays a major roll in the formation of the joint and in which a liquid phase is absent during welding.

Diffusion Welding. Solid-state diffusion welding is a joining method in which metals are welded through the application of pressure and heat. Pressure is limited to an amount that will bring the surfaces to be joined into intimate contact. Very little deformation of the parts takes place. Solid-state diffusion welding does not permit melting of the surfaces to be joined. Once the surfaces are in intimate contact, the joint is formed by diffusion of some element or elements across the original interfaces.

Some of the merits of the process that make it attractive as a method of manufacturing are as follows:

(1) Multiple welds can be made simultaneously.

(2) Welds can be made that have essentially the same mechanical, physical, and chemical properties as the base metal.

(3) Welding can be done below the recrystallizaton temperature of most materials.

(4) The formation of brittle compounds can be avoided provided that proper materials and welding conditions are selected.

(5) For each material combination, there are several combinations of parameters that will produce welds.

(6) Segregation and dilution of alloy or strengthening elements is eliminated. This is important when joining TD nickel.

Diffusion welding is primarily a time and temperature-controlled process. The time required for welding can be shortened considerably by using a high welding pressure or temperature because diffusion is much more rapid at high temperatures than at low temperatures. Both the welding time and temperature often can be reduced by using an intermediate material of different composition to promote diffusion. This procedure reflects the increase in diffusion rate that is obtained by the introduction of a dissimilar metal.

The steps involved in diffusion welding are as follows:

(1) Preparation of the surfaces to be welded by cleaning or other special treatments

(2) Assembly of the components to be welded

(3) Application of the required welding pressure and temperature in the selected welding environment

(4) Holding under the conditions prescribed in Step 3 for the required welding time

(5) Removal from the welding equipment for inspection and/or test.

The preparation steps involved in diffusion welding usually include chemical etching and other cleaning steps similar to those employed during fusion welding or brazing. In addition, the surfaces to be welded may be coated with some other material by plating or

vapor deposition to provide surfaces that will weld more readily. Coatings such as ceramics are sometimes applied to prevent welding in certain areas of the interface. Methods used to apply pressure include simple presses containing a fixed and movable die, evacuation of sealed assemblies so that the pressure differential applies to a given load, and placing the assembly in autoclaves so that high gas pressures can be applied. A variety of heating methods also can be used in diffusion welding. Generally, the temperature is raised by heating with some type of radiation heater. Resistance-spot-welding equipment also is used (Ref. 31). As suggested above, environment during welding is important.

Diffusion-bonded joints have been made in a limited number of nickel alloys using the conditions encompassed by the following ranges:

Temperature – 1600 to 2200 F

Time – 0.2 minute to 23.3 hours

Pressure – about atmospheric to 24,000 psi.

Bonding conditions reported in the published literature are given in Table XIX. Applications for diffusion bending are illustrated in Figures 44 and 45 (Ref. 66).

Deformation Welding. Deformation welding differs from diffusion welding primarily in that a large amount of deformation takes place in the parts being joined. The large amount of deformation makes it possible to produce a weld in much shorter times and frequently at lower temperatures than are possible during diffusion welding. When joining sealed assemblies at elevated temperatures, bonding pressures and atmospheres often differ considerably from room-temperature values because of such factors as outgassing and softening of the materials. Arrangements must be made to control these factors under actual bonding conditions. Welding deformations as great as 95 per cent may be used. The steps involved in deformation welding are very similar to those used in diffusion welding.

Roll welding is a solid-state-deformation-welding process that has been used for the fabrication of structural shapes and sandwich panels (Refs. 71-73). Materials that have been investigated and found to be suitable for this method of fabrication include:

(1) Aluminum Alloys 2024 and 5052

TABLE XIX. SUMMARY OF DIFFUSION-BONDING PROCESSES FOR NICKEL-BASE SUPERALLOYS[a]

| Alloy | Surface Preparation | Bonding Parameters: Time, min | Bonding Parameters: Temperature, F | Bonding Parameters: Pressure, psi | Atmosphere | Reference |
|---|---|---|---|---|---|---|
| Nimonic 90[b] | Degrease, abrasion (500-grit abrasive) | 15 | 2000 | 4,000 | Protective | 67 |
| TD nickel | -- | 1/5 | 2200 | 10,000 | Inert | 68 |
| TD nickel | -- | 1440 | 2050 | Low | -- | 68 |
| TD nickel | Degrease | 1/6 | 2200 | 20,000 | Inert | 69 |
| TD nickel | Acetone and water | 1 | 2000 | 12,500 | Vacuum or inert | 66, 70 |
| TD nickel | Acetone and water | 1 | 2150 | 7,500 | Vacuum or inert | 66, 70 |
| TD nickel[c] | Polish, degrease, pickle, rinse | 90 | 2000 | 9,000 | -- | 64 |

(a) Stop weld not used.
(b) 0.002-in. nickel-foil intermediate used.
(c) Includes lap joints and lap joints with nickel- and molybdenum-foil intermediates.

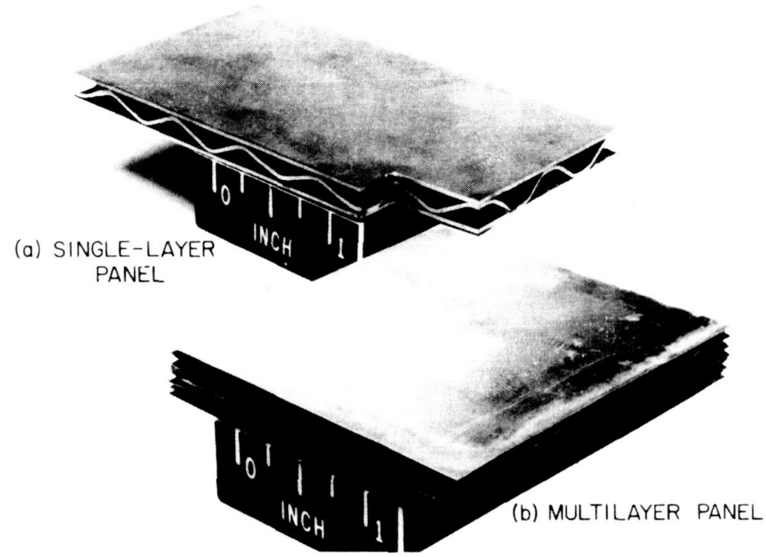



FIGURE 44. DIFFUSION-BONDED STRUCTURAL PANELS (REF. 66)

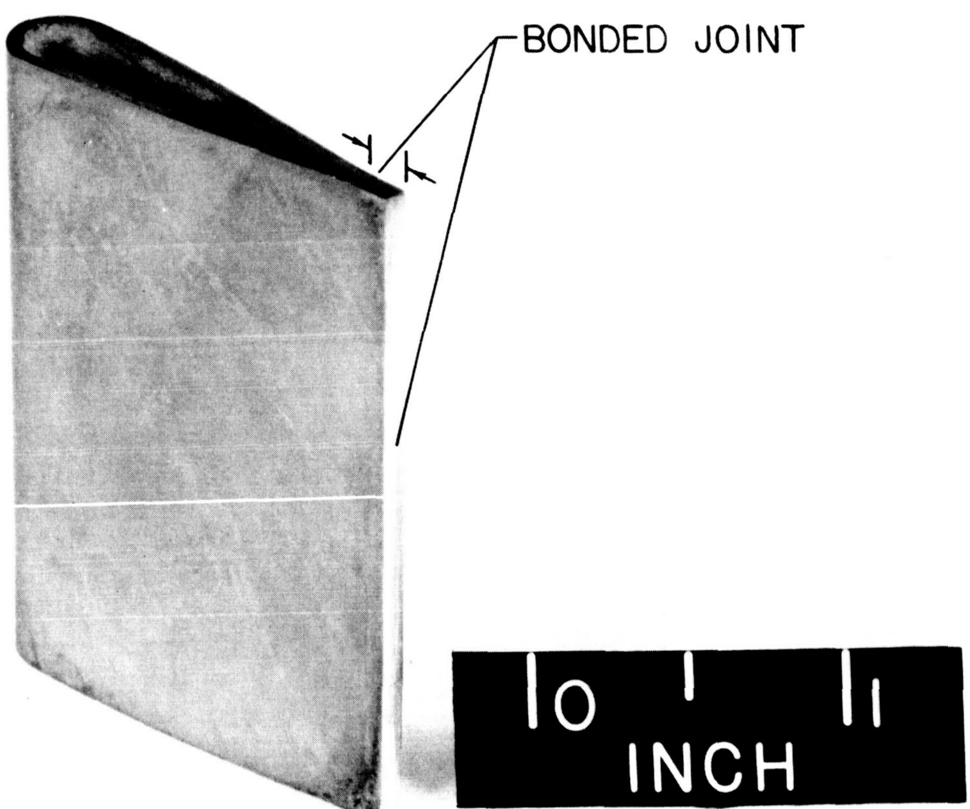



FIGURE 45. DIFFUSION-BONDED JET-ENGINE BLADE (REF. 66)

(2) Titanium – alpha and alpha-beta alloy
(3) 300 series stainless steels
(4) PH 15-7 Mo precipitation-hardening stainless steel
(5) René 41, Inconel, nickel-base alloys
(6) Refractory metals – tantalum and columbium, molybdenum, tungsten.

Examples of products made by roll welding are illustrated in Figure 46 (Refs. 71, 74).

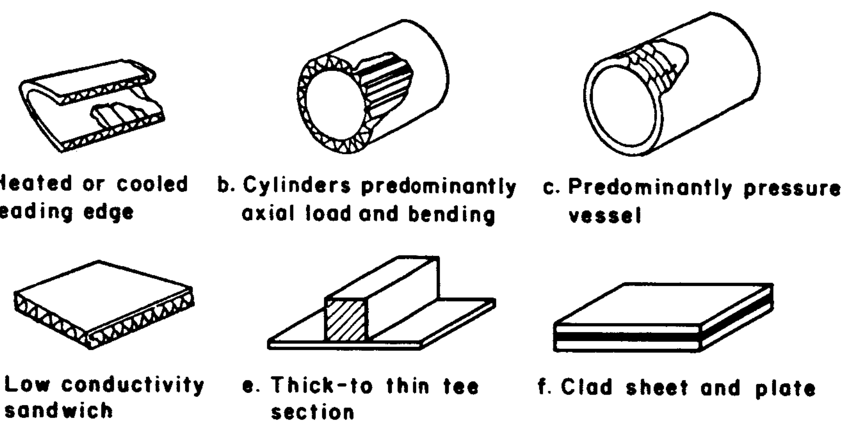



FIGURE 46. TYPICAL APPLICATIONS OF ROLL-WELDED STRUCTURES (REFS. 71, 74)

Pressure gas welding (Refs. 75-77) is a welding process in which the joint is produced simultaneously over the entire area of abutting surfaces, by heating with gas flames and by the application of pressure, without the use of filler metal. Pressure gas welding may or may not be a solid-state-welding process, depending on the actual welding procedure used. The two modifications of the process in common use are the closed-joint and the open-joint methods. In the closed-joint method, the clean faces of the parts to be joined are abutted together under pressure and heated by gas flames until a predetermined upsetting of the joint occurs. This method of pressure gas welding has been used only experimentally for welding a limited number of nickel-base alloys (Ref. 78). In the open-joint method the faces to be joined are individually heated by the gas flames to the melting temperature and then brought into contact for upsetting. There are no known applications of the open-joint method for welding

nickel alloys. The process in both modifications is ideally adapted to a mechanized operation, and practically all commercial applications are either partially or fully mechanized. The process also is adaptable to the welding of low- and high-carbon steels, low- and high-alloy steels, and several nonferrous metal alloys.

Pressure gas welding produces a forged butt weld by upsetting the faying surfaces under heat and pressure. The heating system in one facility consists of a multiorifice circular oxyacetylene torch equipped with suitable pressure regulators and flowmeters to provide a controlled heating rate at the joint. The circular torch is oscillated so the individual pinpoint flames are oscillated circumferentially around the joint to avoid local overheating. The welding pressure is supplied by a hydraulic system of a size sufficient to produce the required forging pressures. Welding pressures vary depending on the material and weld area. An overall view of a pressure-gas-welding machine is shown in Figure 47 (Refs. 77, 78). Although the equipment used for pressure gas welding is a conventional machine for heating and applying pressure, details of the equipment such as the circular heating-torch design are considered proprietary.

A typical pressure-gas-welding cycle is as follows:

(1) The parts to be welded are aligned in the machine.

(2) A controlled welding force is applied.

(3) The torch is ignited.

(4) Heating is continued until sufficient forging has been produced to upset the joint and predetermined amount to complete the joint.

(5) The gas flame is extinguished.

(6) Hydraulic welding force is released.

(7) The part is removed from the machine after cooling to a predetermined temperature.

After welding, the completed weldments are heat treated as required.

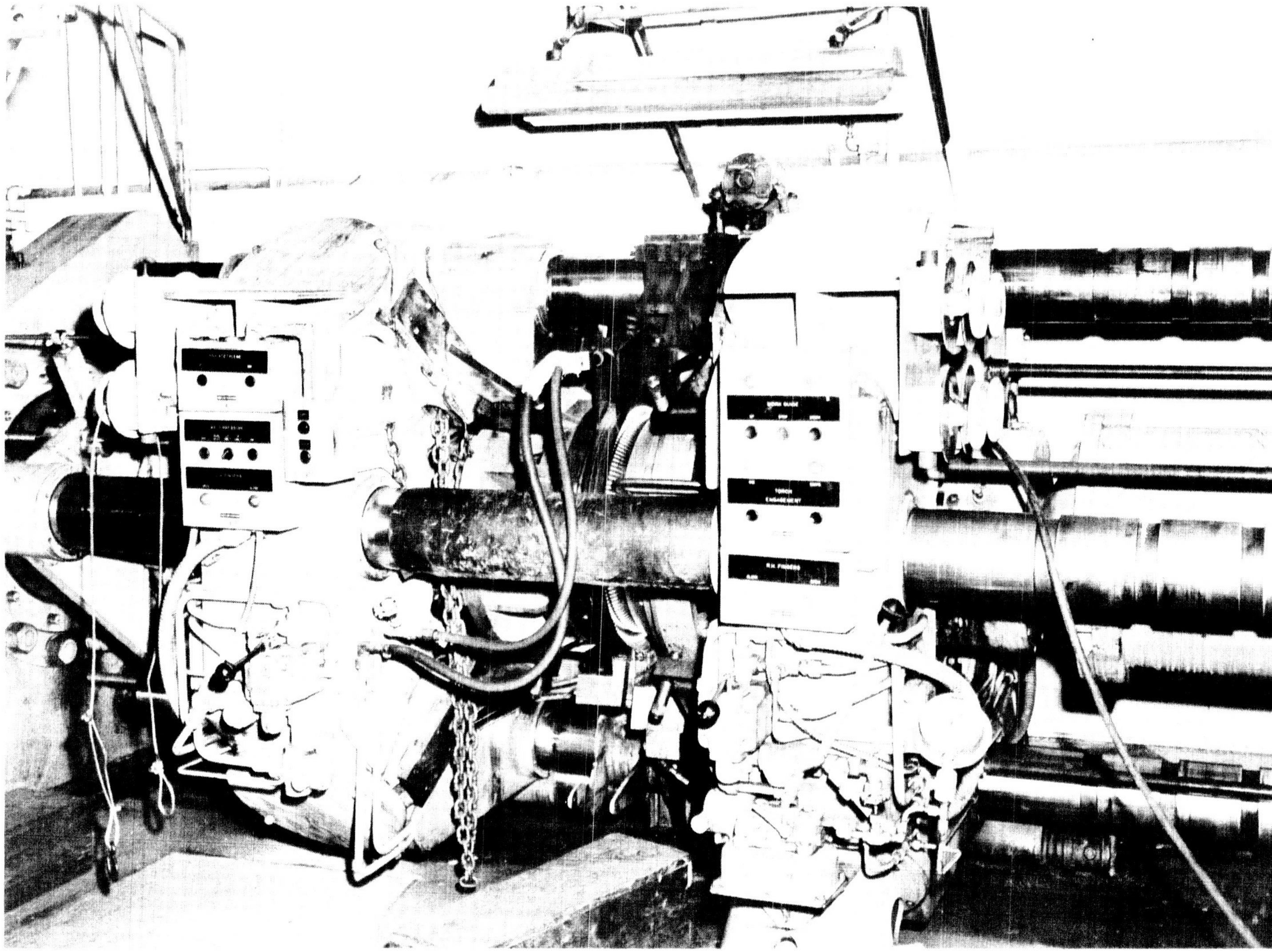


FIGURE 47. APPARATUS FOR GAS PRESSURE WELDING (REF. 77)

## BRAZING AND SOLDERING

Nickel and nickel-base alloys are selected for applications that require either good corrosion resistance or good corrosion resistance combined with useful mechanical properties at elevated temperatures. Brazing is a suitable method for joining parts or assemblies to meet these requirements. Soldering also is used, but the uses of soldered joints are limited to low-temperature-service application.

Brazing is performed by heating the region of the joint and using brazing filler metals to complete the joint. The brazing definition consists of three parts: (1) the joining of two or more parts by heating to temperatures of 800 F or above, (2) the use of a filler metal having a melting temperature range that is below that of the base metal, and (3) the wetting of the base-metal surfaces by the filler metal. Soldering is similar to brazing, but the base metals are heated to temperatures below 800 F. Heating can be performed with torches, furnaces, radiation heaters, self-resistance heating, and by other means.

When selecting a brazing procedure it is important to consider the behavior of (1) the base metal and (2) the brazed joint during brazing and under service conditions. Some nickel and nickel-base alloys can be brazed using conventional brazing procedures, while other alloys require great care. During brazing, residual or applied tensile stress should be kept as low as possible. Certain molten brazing filler metals can cause stress-corrosion cracking. Also, inherent stresses present in the age-hardenable alloys can lead to stress-corrosion cracking. Stress relieving or annealing prior to brazing is advisable. Special treatments, filler metals, or procedures also are necessary for some alloys. For example, nickel alloys that contain chromium, aluminum, or titanium have tenacious oxides on their surfaces. These oxides form easily and cannot be reduced readily by pure hydrogen or by fluxing.

Brazing filler metals for nickel and nickel-base alloys include: (1) filler metals that are normally used for brazing ferrous materials and (2) special-purpose filler metals developed by individual organizations. Some typical brazing filler metals for nickel and nickel-base alloys are listed in Table XX (Refs. 10, 79, 80). The proper filler is determined by service requirements, compatibility of the brazing filler metal with the base metal at brazing temperatures, availability of suitable brazing alloys, and postbrazing heat-treating requirements.

TABLE XX. COMMONLY USED FILLER METALS FOR BRAZING NICKEL AND NICKEL-BASE ALLOYS (REFS. 10, 79, 80)

| Composition, weight per cent | | | | | | Temperature, F | | |
|---|---|---|---|---|---|---|---|---|
| Ag | Cu | Zn | Cd | Ni | Others | Solidus | Liquidus | Brazing Range |
| | | | | | Silver-Brazing Alloys | | | |
| 35 | 26 | 21 | 18 | -- | -- | 1125 | 1295 | 1295-1550 |
| 45 | 15 | 16 | 24 | -- | -- | 1125 | 1145 | 1145-1400 |
| 50 | 15.5 | 16.5 | 18 | -- | -- | 1160 | 1175 | 1295-1550 |
| 50 | 15.5 | 15.5 | 16 | 3 | -- | 1195 | 1270 | 1270-1500 |
| 56 | 22 | 17 | -- | -- | 5.0Sn | 1145 | 1205 | 1205-1400 |
| 60 | 30 | -- | -- | -- | 10.0Sn | 1095 | 1325 | -- |
| | | | | | Copper-Brazing Alloys | | | |
| -- | 99.90 | -- | -- | -- | 0.04O | -- | 1981 | 2000-2100 |
| -- | 99.92 | -- | -- | -- | -- | -- | 1981 | 2000-2100 |
| | | | | | Nickel-Brazing Alloys | | | |
| -- | -- | -- | -- | 93 | 3.5Si, 2B | -- | -- | 1950-2150 |
| -- | -- | -- | -- | 91 | 4.5Si, 3B | -- | -- | 1850-2000 |
| -- | -- | -- | -- | 90 | 10P | -- | -- | 1750-1950 |
| -- | -- | -- | -- | 82 | 7Cr, 3Fe, 4Si, 3B | -- | -- | 1850-2000 |
| -- | -- | -- | -- | 72 | 16Cr, 4Fe, 4Si, 3.8B | 1850 | 1950 | 1900-2100 |
| -- | -- | -- | -- | 39 | 33Cr, 24Pd, 4Si | 1820 | 2150 | 2150 |

Brazing and soldering alloys should not interact excessively with the base metal. Much effort has been expended to overcome problems resulting from interactions of nickel-base filler metals with nickel-alloy-base metals. No completely satisfactory solutions have been found. Brazing filler-metal alloys that contain phosphorus, aluminum, and magnesium are not used because these elements have a strong tendency to form brittle compounds or alloys. Lead, bismuth, and antimony, frequent constituents of solders and threading compounds, also have embrittling effects on nickel and nickel-base alloys at elevated temperatures. Nevertheless, conventional solders are often used. Tin also is used for some highly corrosive service applications.

Cleanliness is extremely important when brazing nickel and nickel-base alloys. This applies to the base metal, filler metal, atmospheres, and fluxes. All elements that cause contamination or

interfere with brazing should be eliminated. All forms of surface dirt such as paint, oil, chemical residues, and scale should be removed using suitable procedures such as those described earlier in the section on cleaning. Formation of refractory oxides on nickel-base alloys that contain elements such as aluminum and titanium should not be permitted. Procedures that prevent the formations of oxides before and during brazing include special treatments of the surfaces to be joined or brazing in a controlled atmosphere. Surface treatments include copper plating, nickel plating, and reducing the oxides to metallic form. Dry, oxygen-free atmospheres that are used include inert gases, hydrogen, and vacuum. Brazing atmospheres, whether gases or vacuum are used, should be free from harmful constituents, such as sulfur, oxygen, and water vapor.

Brazing flux is needed to "combine with, dissolve, inhibit, or otherwise render ineffective those unwanted products of the brazing operation which would otherwise impair the braze or totally prevent brazing (Ref. 10)". This applies to soldering fluxes also. Fluxes are not designed for primary cleaning, which should be performed by conventional cleaning operations. There are no known fluxes suitable for the nickel-base alloys that contain large amounts of titanium and/or aluminum. For nickel-base alloys having only minor amounts of aluminum or titanium, brazing fluxes containing chlorides, fluorides, borates, and wetting agents can be used. These fluxes should be selected with care depending on the filler and base metals and brazing conditions. For soldering operations, acid fluxes only are recommended. The cleaning actions of rosin fluxes are too mild, so they are not used. As in welding, it is important to remove fluxes after the joining operation.

Equipment for brazing nickel and nickel-base alloys is of the same type that is used for brazing other common material. Standard equipment is available commercially for torch, furnace, induction, resistance, and vacuum brazing. The equipment should be capable of controlling important factors such as heating and/or cooling rate, temperature, time at temperature, and atmosphere when desired.

Heating Methods. Many methods are used for heating the parts to brazing or soldering temperatures. The entire joint must be heated uniformly for a time sufficient for the alloy to flow and fill the joint area. Heating methods and procedures are summarized in the published literature (Ref. 10) and below. The selection of heating method will depend upon factors such as size of assembly, configuration of the parts, types of metals involved, production requirements, and available equipment.

For manual brazing, gas torches or radiation heaters are used. Air and city gas, air and other fuel gases, oxyacetylene, or oxyacetylene and other gases may be used for torch brazing. A large, soft reducing flame is preferred. The flame is played on the work to heat the joint area to a uniform temperature of 50 to 100 F higher than the melting temperature of the brazing alloy employed. Then the brazing alloy is applied. The alloy will flow toward the hotter part if the parts are clean. When the alloy has flowed completely, the flame should be removed and the joint allowed to cool undisturbed. Solidification of the alloy can be observed by a sudden change from very shiny to less shiny appearance of a fillet. At this time the joint has very low strength and if moved a cracked joint might result.

Furnaces, either electrical, oil or gas fired, may also be used for brazing. Usually such brazing is done in large batches. Careful control of temperature is necessary to prevent overheating or underheating. If the furnace is too small to heat the parts rapidly, an oxygen-free atmosphere is helpful in extending the life of the flux. Induction heating also is a good heating method. Very heavy parts can be heated so rapidly that the outside surfaces become hot without appreciable heating of the center. In such instances thermal stresses can be developed and cause stress cracking. Resistance heating also is used for small parts and for the assembly of small parts to large parts where pressure on the parts can be applied. Salt-bath brazing may be employed, but is seldom applied to nickel and nickel alloys. Metal-bath brazing finds limited application in fine wire and very small parts. Heating for soldering can be performed in the same manner as for brazing in addition to the many forms of manual soldering tools that are available commercially.

Additional details of brazing and soldering procedures are determined by the particular alloy, base metal, and intended service. Producers of the base metal and brazing filler-metal alloys, and the published literature should be consulted for additional details.

Brazed- and soldered-joint quality are evaluated by conventional methods (Ref. 10). However, when the assembly is intended for elevated-temperature service, quality requirements are more rigid. Additional tests usually are required.

Detailed information on properties of brazed and soldered connections are not included here. Published literature, standard handbooks, and manuals should be consulted for this data.

Applications. Practically every form of brazing has been used for joining nickel and nickel-base alloys for a broad range of service. In recent years considerable information has been developed for applications involving brazing for assemblies to operate at high temperatures. An inherent problem when brazing many high-temperature alloys with nickel filler metals is the harmful effect of the high temperatures on base metals. Reaction of the brazing filler metals with the base metal also is a problem with some alloys.

Quantitative data on the effects of brazing thermal cycles on base-metal strength show that strength losses and microstructural changes occur to varying degrees. A study of eight superalloys showed that generally the weakest high-temperature alloys had the greatest strength losses. The strongest alloys had the least loss of properties and in most instances responded to postbrazing heat treatments (Ref. 81).

The good heat-transfer characteristics of nickel make it a useful material for heat exchangers. One difficulty encountered, however, is intergranular penetration by the brazing alloy, particularly when brazing thin sheet. Many of the conventional brazing alloys that are recommended for use with nickel-base alloys contain nickel, chromium, silicon, iron, and boron. Nickel is the major element. A widely used brazing filler metal contains 73.25 per cent nickel, 14 per cent chromium, 3.5 per cent boron, 4 per cent silicon, 4.5 per cent iron, and 0.75 maximum carbon. Wide experience developed by users has taught how to minimize the effects of base-metal filler-metal reactions. For brazing thin nickel-base alloys, however, a standard brazing alloy containing 77 per cent nickel-13 per cent chromium-10 per cent phosphorus also is recommended for some applications. This alloy has low solubility with nickel-base alloys and erosion of the base metal can be controlled more readily (Ref. 10). Also, a 65 per cent nickel, 23 per cent manganese, 7 per cent silicon, and 5 per cent copper alloy has been developed to cope with the penetration problem (Ref. 81). The manganese addition inhibits intergranular attack by nickel-phosphorus and nickel-silicon alloys.

Brazing appears to be a process well suited for joining TD nickel. Numerous brazing filler alloys are being investigated for joining this alloy for service temperatures in the 1400 to 2400 F range. Brazing alloys that provide adequate strength, good flow and wetting behavior, and a range of brazing temperatures have been identified (Ref. 57).

Diffusion effects at 2000 F and preferential oxidation of diffusion zones are primary problems.

Examples of products made by brazing of nickel and nickel-base alloys are shown in Figure 48 (Refs. 79, 80, 82).

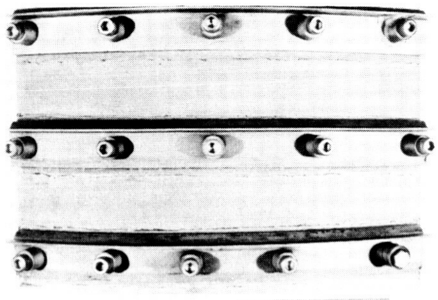
## DISSIMILAR METALS

Sometimes it is necessary to join the nickel-base alloys to alloys of lower nickel content or to other metals such as stainless steel or carbon steel. This may be done by welding, brazing, soldering, or it may be done mechanically. The preferred methods are welding and brazing. Soldering is usually suitable only for joints that carry very little or no load at room temperature.

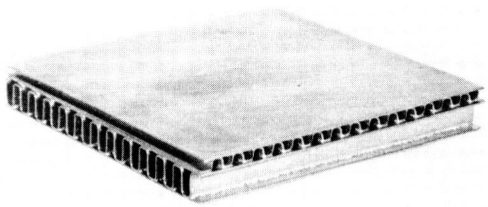
The problems that arise when joining dissimilar metals depend mainly on the difference in composition between the alloys. If they are similar or are metallurgically compatible over a wide composition range, problems will not be great, assuming that good welding practice is used. An example of the ideal metallurgical situation is the welding of pure nickel to Monel. These metals are completely compatible. Consequently, they can be welded to one another by any process using any compatible filler material without difficulty. Metals that are often joined to nickel and nickel-base alloys are listed in Table XXI (Refs. 8, 9).

In other situations, dilution of the nickel-base alloy with a dissimilar metal during welding can be tolerated only to a limited degree (Ref. 83). If stainless steel filler wires are used to join Monel to austenitic stainless steel, any significant copper pickup from the Monel will cause the weld to become hot short and crack in the weld. Thus stainless steel filler wire should be avoided for this combination when processes that cause much dilution are used. Likewise, a Monel filler wire is not useful because chromium from the stainless will cause cracking. A special Inconel filler wire or nickel are best, but are not foolproof.

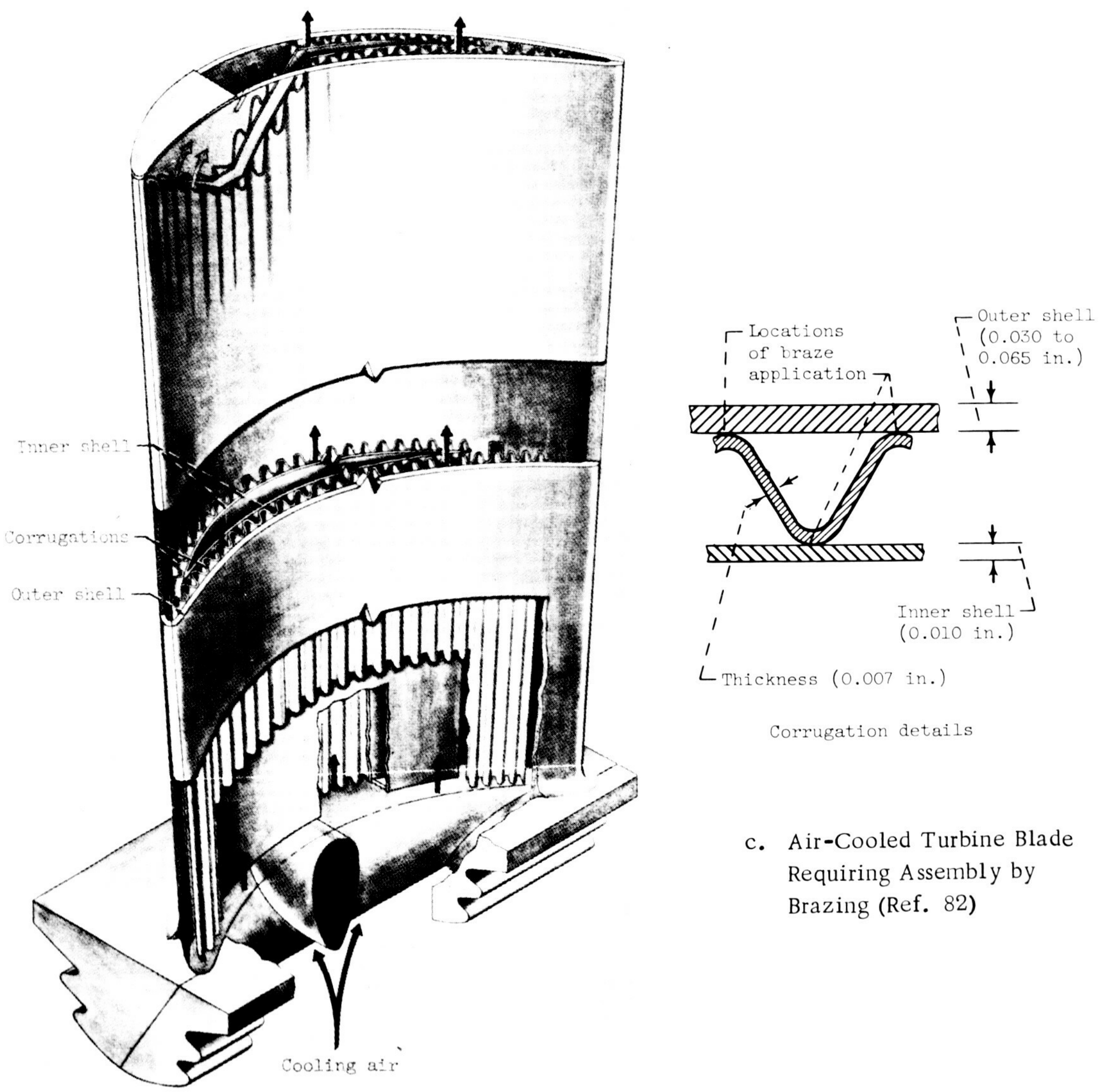
Thus, it is apparent that the dilution obtained during the welding of nickel-base alloys to other metals is very important. Processes that result in a minimum of dilution should always be used. Manipulation of the arc to impinge mainly on the base metal that is nearest in composition to the filler wire will assist in minimizing dilution. Suppliers of filler wire and electrodes should be consulted before a



a. Simulated Section of René 41 Compressor Casing Vacuum Brazed with J-8600 (Ref. 79)



b. Inconel 600 Air-to-Air Heat Exchanger (Ref. 80)




c. Air-Cooled Turbine Blade Requiring Assembly by Brazing (Ref. 82)

FIGURE 48. EXAMPLES OF NICKEL-BASE-ALLOY PRODUCTS FABRICATED BY BRAZING

TABLE XXI. COMMONLY WELDED DISSIMILAR-METAL COMBINATIONS OF NICKEL AND NICKEL-BASE ALLOYS (REFS. 8, 9)

| |
|---|
| Monel 400 to: |
| Steel |
| Low-alloy steel |
| Stainless steel (304) |
| 70/30 copper-nickel |
| Hastelloy B |
| Nickel 200 to: |
| Steel |
| Low-alloy steel (8630) |
| Stainless steel (304) |
| Monel 400 |
| 70/30 copper-nickel |
| Hastelloy B |
| Inconel 600 or Incoloy 800 to: |
| Steel |
| Low-alloy steel (8630) |
| Stainless steel |
| Monel 400 |
| Nickel 200 |
| 70/30 copper-nickel |
| Hastelloy B |

choice is made for any particular dissimilar-metal combination. The following weld compositions should be avoided:

(1) A ferritic weld deposit if dilution by nickel, chromium, or copper is to be encountered

(2) The 18-8-type weld deposit if dilution by more than 3 per cent copper is to be encountered

(3) A high-carbon Monel deposit if dilution by iron is to be encountered

(4) Any Monel deposit if dilution by more than 6 to 8 per cent chromium is anticipated

(5) The 18-8-type deposit if dilution by nickel and chromium is sufficient to result in the crack-sensitive 35Ni-15Cr weld composition.

Arc welding of Inconel to Type 304 stainless steel, carbon steel, and to itself has been investigated (Ref. 84). Base-metal plate thicknesses from 0.75 to 2.63 inches were welded using the shielded-metal-arc, inert-gas tungsten-arc, and inert-gas metal-arc processes. Welds were obtained by all processes that met the stringent requirements for nuclear-power-plant service. Included in the published data are strength at room temperature and at 650 F, hardness, and bend ductility. This study also included overlaying of Inconel on other base metals. A similar study was made of the welding of heavy Inconel plate to carbon steel utilizing specific nickel-base electrodes, MIL-4N85 for welding with covered electrodes and MIL-EN87/RN87 for gas metal-arc welding (Ref. 36). The weld deposit compositions of these electrodes for use when welding or overlaying are given here.

| Electrode | Composition, per cent | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Ni | Cr | Fe | Mn | Cb+Ta | C | Ti | Si | S | Cu | Co |
| MIL-4N85 | 67.0 | 14.7 | 7.5 | 7.7 | 2.0 | 0.04 | 0.40 | 0.50 | 0.007 | 0.03 | 0.07 |
| MIL-EN87/RN87 | 72.0 | 20.0 | 1.0 | 3.0 | 2.6 | 0.03 | 0.30 | 0.30 | 0.009 | 0.02 | 0.04 |

Crack- and porosity-free welds were obtained under every condition examined; position, heat treatment, high restraint, and use over other filler-metal-alloy weld deposits.

Another electrode was reported useful for making transition welds between Inconel and stainless steel (Ref. 85). A titanium-manganese modified Inconel weld wire was used with the gas metal-arc process to produce high-quality welds in heavy plate. Age-hardened Inconel W, 1-inch-thick, has been welded to Inconel of the same thickness using the manual and gas tungsten-arc processes. For the production of retorts for high-temperature furnaces, Hastelloy X is welded to itself, to Inconel, and to mild steel. (Ref. 86). The same practice is used for the dissimilar-metal systems as when welding Hastelloy X to itself, but a different filler metal is used (Inco-Weld "A"). Heat input is kept at a minimum by: careful joint design, single-pass welding, minimum weaving, high travel speeds. The thicknesses welded are 0.25 and 0.38 inch.

Two considerations are important when welding nickel-base alloys to other metals, viz., dilution of the weld metal, and proper choice of the filler-metal. These two factors are strongly interrelated and have led to the development of new and altered filler metals as indicated. The welding of the age-hardenable nickel-base alloys to other metals is not well covered in the literature. Such joints are made, however, with considerable success as long as the accepted procedures and proper filler metals are used. Hastelloy W has been used widely as a filler metal for welding dissimilar combinations. It was developed for this purpose. The composition of Hastelloy W is essentially the same as that of Hastelloy B, but with 5 per cent additional chromium. This composition provides an ideal matrix when used to weld many different dissimilar age-hardenable-alloy combinations.

## JOINT QUALITY

Joints in nickel and nickel-base alloys often may contain undesirable features that will interfere with proper operation in service. Suitable inspection techniques and repair methods must be used that will detect those features that are undesirable and permit their repair. It is also desirable to determine the causes of the undesirable features so proper remedial and repair procedures can be developed.

## INSPECTION

Joints in nickel and nickel-base alloys usually are inspected by several methods. Nondestructive inspections are almost always performed but destructive inspection generally is not performed on completed product joints. It is often necessary and desirable to check changes in dimensions that may have resulted from welding. The visual- and measurement-type inspections performed for this purpose may also include checks of weld-joint profile and measurements of the weld thickness. Various inspection procedures also are used to insure that the joints produced are of satisfactory quality. The most commonly used techniques in this area include visual, dye penetrant, and X-ray techniques. Various types of leak tests are also used on components designed to contain gases or fluids.

## DEFECTS

The definition of joint defects is arbitrary. Many years of experience have been gained with welding codes and specifications that either prohibit or allow certain features characterized as defects. Features recognized as defects are generally limited in accordance with conservative practices. This approach to defects has been quite successful in the past, but is of some concern when dealing with many of the newer materials being used in various types of fabrication. This concern is based on the belief that the removal of certain types of features classified as nonallowable defects often results in more damage to the serviceability of a structure than the damage that potentially might have been done by allowing the feature to remain. The reluctance of many welding engineers to repair certain features is based on this feeling, not on a desire to make the welding job easier.

The fabrication of defect-free welds is highly dependent on the quality requirements of applicable specifications and on the inspection methods that are used. For example, hardly any welding code or specification allows cracks in a weld. However, cracked welds can and do get into service if inspection methods that will insure detecting all cracks present in a weld are not required.

The only reliable way to determine what weld features are truly defects is to evaluate the effects of such features in a test program. Such an evaluation must include tests that are representative of the service conditions. Many defectlike weld features have no effect on

the static-tension properties of the weld. However, these same features may be found to degrade performance seriously in a fatigue test.

With the knowledge currently available about the performance of fusion weldments, a conservative engineering approach to defects should be followed. Typical arc-weld features that are sometimes classified as defects are shown in Figure 49.

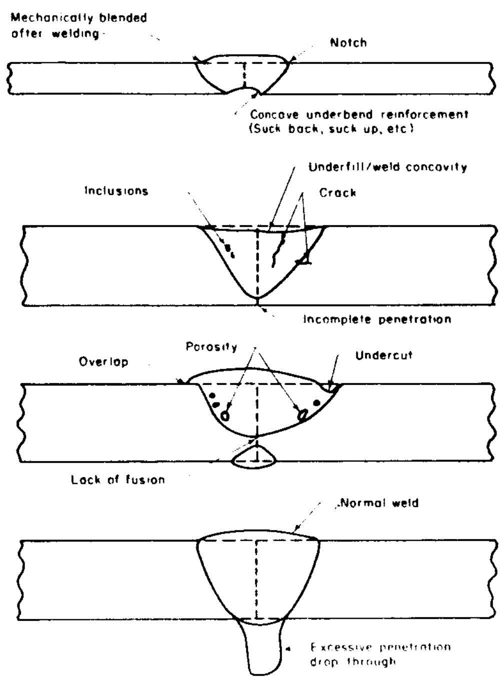



FIGURE 49. ARC-WELD DEFECTS

Porosity. Porosity has been encountered to some extent in fusion welds in nickel and nickel-base alloys. Measures to control cleanliness and employment of good welding techniques have successfully reduced the occurrence of porosity. Specific identification of the various causes of porosity is still lacking. Some factors known to cause porosity in nickel and nickel-base alloy welds include:

(1) Improper filler metals
(2) Incorrect arc length
(3) Low welding speed
(4) Insufficient sheet thickness
(5) Air in shielding gas
(6) Moisture.

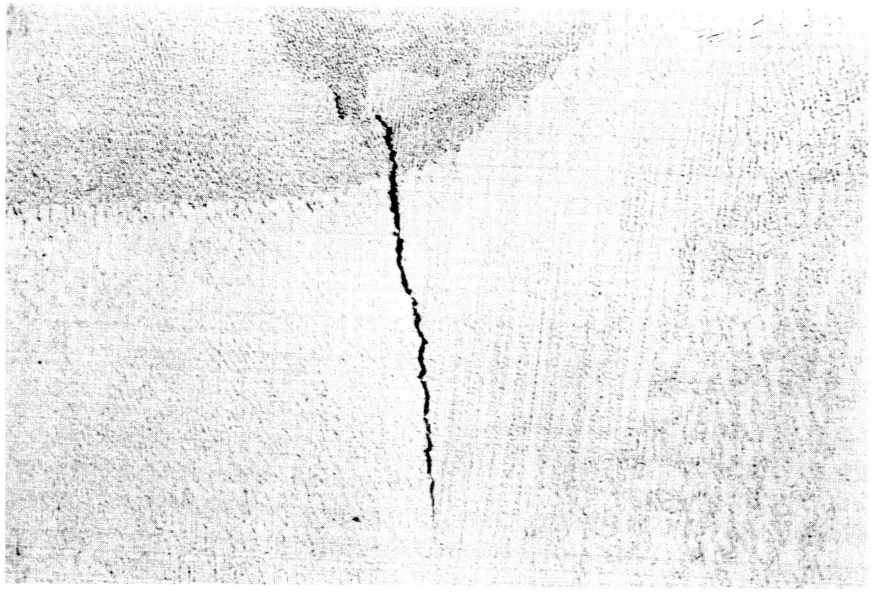
Porosity in welds can be controlled if the procedures that have been developed by the many investigations in the area are followed.

Folds and Surface Pits. Fluorescent and dye-penetrant indications are obtained from folds and pits at the surface of the weld metal. Often, these features are not considered detrimental to weld quality. They do not necessarily indicate the presence of subsurface cracks or porosity (Ref. 41).

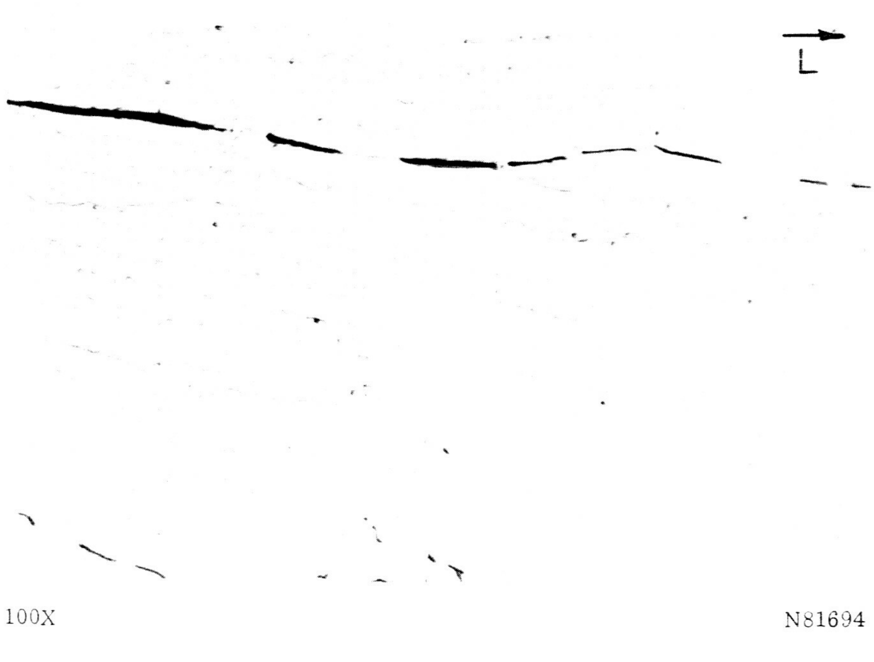
Fissures. Intergranular cracking is a problem in a wide range of metals and alloys. The degree of cracking ranges from readily detected macrocracks to nearly undetectable microcracks. In nickel-base alloys these microcracks are usually called fissures. For many applications the presence of weld-metal fissures is not considered serious. However, in nuclear applications, steam-power plants, and numerous aerospace applications, fissures are a critical problem because the specifications used prohibit their presence. In a recent study (Ref. 88) intergranular fissuring was attributed to grain-boundary segregation that was present in large amounts when (1) the original impurity concentration in the alloy was high and (2) when large grains were formed in the microstructures at high temperatures. Figure 50 illustrates the appearance and small size of typical weld fissures in a nickel-chromium-iron alloy (Ref. 87).

Strain-Age Cracking. Strain-age cracking occurs in the age-hardenable high-temperature nickel-base superalloys during the initial heat treatment following fabrication by welding or cold working. The problem is particularly intense when repair welding is conducted on aged material. This behavior presents a serious limitation to the use of these alloys in applications where they are otherwise well suited. The cracks are relatively large, with the greater part of the crack in the base metal (Ref. 88).

Strain-age cracking occurs only in annealed material during initial heating in the aging range after fabrication by cold work and/or welding aged material where at least one area, such as an as-deposited weld, is in the solution-annealed condition. Strain-age cracking is rarely, if ever, encountered in solid-solution-hardening nonaging nickel-base alloys such as Inconel and Nimonic 75. Strain-age cracking in Inconel X and René 41 has been investigated and appears to be related to metallurgical reactions during aging that result in grain-boundary embrittlement. With René 41 sheet, studies of



100X N80340




100X N81694

FIGURE 50. WELD FISSURES IN A NICKEL-CHROMIUM-IRON ALLOY (REF. 87)

manual and automatic arc-welding techniques for minimizing strain-age cracking showed that:

(1) Automatic welds generally are less susceptible to strain-age cracking than manual welds.

(2) High-heat-input gas-tungsten-arc welds are more susceptible to strain-age cracking than low-heat-input welds.

(3) Material air-cooled from the solution-treating temperature is more crack susceptible than water-quenched material.

(4) Aged material is the most crack-susceptible condition investigated (1950 F, 2200 F, as-quenched in water and air, and 1950 F, 2200 F, air and water quenched plus 16 hr, 1400 F age).

(5) Preheating at 600 F prior to welding showed no reduction in crack susceptibility on subsequent aging at 1400 F. Reduction of residual welding stresses was not apparent. No advantage was gained from the reduced cooling rate of the heat-affected zone.

(6) Shot peening was very effective as a means for reducing strain-age cracking during aging of 0.032- and 0.500-inch material under test conditions. Residual stresses were reduced to a level where crack initiation was impossible, despite tensile stresses generated by contraction during aging.

(7) Localized aging appears to be effective for eliminating strain-age cracking under some conditions.

(8) Tests conducted on 1/2-inch-thick plate indicate that strain-age cracking can be avoided if welded specimens are stress relieved by heating to a minimum temperature of 1650 F for 1 hour at a rate of no less than 270 F per minute. The success of rapid heating is considered a result of:

    (1) Slight compressive stresses generated on the surface of the part due to thermal gradients

(2) Delay of gamma prime precipitation until the material is in a more ductile condition

(3) Insufficient time for brittle grain boundaries to form before residual stresses in the part are reduced to a safe level.

Defects in Resistance Welds. Characteristics described as defects in resistance welds are difficult to assess. Defects in resistance welds are generally subdivided into external and internal defects. With the exception of cracks that are exposed to the exterior of the sheets and that are obviously undesirable, the remaining external defects are probably considered as such because they are indicative that the welding conditions may not have been exactly right. External defects in this category are sheet preparation, surface pits, metal expulsion, tip pickup, and excessive indentation. With internal defects, cracks are obviously undesirable, but there is very little evidence that porosity in minor amounts is harmful to properties. The same is true of either insufficient or excessive penetration. Typical defects in resistance spot and seam welds and their causes are given in Figure 51 (Ref. 89).

## REPAIRS

During the development of procedures for joining nickel and nickel-base alloys, consideration should always be given to the possibility that repairs may be necessary. This is especially true in the case of the solid-solution-hardening and age-hardening alloys, because the cost of the base metal and preparing it for joining is very high. Also, the complex structures usually involved are not amenable to complete stress analysis prior to welding.

Available information on joining repairs is practically limited to making repairs or developing repair procedures for arc-fusion welds by arc-fusion welding. The following discussion, therefore, is confined to repair of fusion welds by arc welding.

Repair of weldments is not desirable. However, it is an almost inevitable occurrence in production operations. An aspect of repair welding is determining what caused the defect that must be repaired. This is important, not only for its feedback value to minimize the need for subsequent repairs, but also to determine a suitable repair-welding procedure.

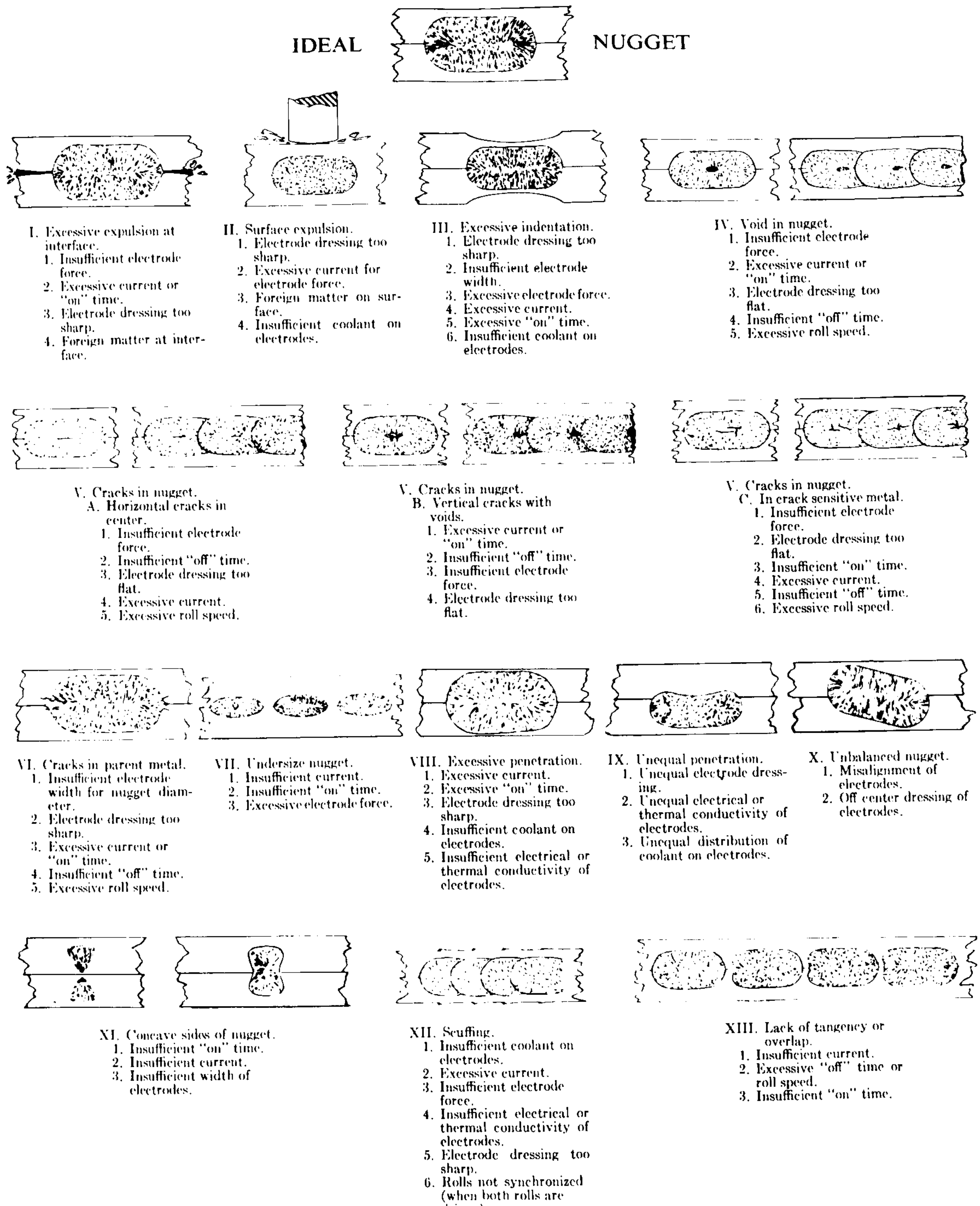
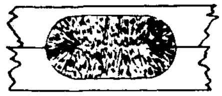
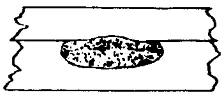



FIGURE 51. COMMON DEFECTS IN RESISTANCE SPOT AND SEAM WELDS AND THEIR CAUSES (REF. 89)

Prevalent causes in order of importance.
Courtesy of Allegheny Ludlum Steel Corporation.

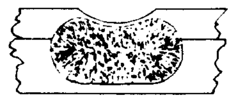
IDEAL  NUGGET



I. Lack of penetration in thin sheet.
1. Electrode dressing too flat on thin sheet.
2. Excessive electrode force.
3. Excessive electrical or thermal conductivity of electrode on thin sheet.
4. Insufficient electrical or thermal conductivity of electrode on heavy sheet.

II. Lack of penetration in both sheets.
1. Electrode dressing too flat.
2. Excessive electrode force.
3. Insufficient current.
4. Insufficient "on" time.

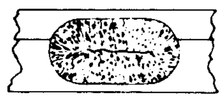
III. Unbalanced nugget.
1. Misalignment of electrodes.
2. Off-center dressing of electrode faces.



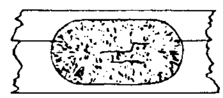
IV. Excessive indentation.
1. Electrode dressing too sharp at indentation.
2. Excessive electrode force.
3. Excessive current or "on" time.
4. Insufficient width of electrode at indentation.

V. Excessive penetration.
1. Electrode dressing too sharp on thin sheet.
2. Insufficient electrode force.
3. Excessive current or "on" time.
4. Insufficient electrical or thermal conductivity of electrode.
5. Insufficient coolant.

VI. Void in nugget.
1. Insufficient electrode force.
2. Excessive current.
3. Excessive "on" time or roll speed.
4. Electrode dressing too flat.
5. Insufficient "off" time.



VII. Cracks in nugget.
A. Horizontal cracks at center.
1. Insufficient electrode force.
2. Insufficient "off" time.
3. Electrode dressing too flat.
4. Excessive current or "on" time.



VII. Cracks in nugget.
B. In crack sensitive metal.
1. Insufficient electrode force.
2. Electrode dressing too flat.
3. Insufficient "off" time.
4. Insufficient "on" time.

VIII. Cracks in parent metal.
1. Insufficient electrode width for nugget diameter.
2. Electrode dressing too sharp.
3. Excessive roll speed.
4. Excessive current or "on" time.
5. Insufficient "off" time.
6. Insufficient electrode force.

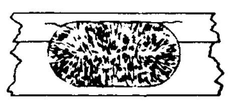


FIGURE 51. (CONTINUED)

The repair of the nonaging nickel-base alloys does not usually present serious problems. Analysis of the cause of the defect, its complete removal, and then repair welding utilizing the original procedure altered to eliminate the cause of the defects will usually suffice. Most of the solid-solution- and age-hardening nickel-base alloys are much more difficult to repair weld. The extra thermal cycling due to rewelding and the heat treatments necessary must be carefully developed for the situation at hand.

A few general rules applicable to the repair welding of all nickel-base alloys are outlined below. If they are followed, problems will be minimized.

(1) Inspect for repairable flaws immediately after joining and before any subsequent treatment. Multipass welds and products requiring multiple joints should be inspected after each step in the joining operation.

(2) Determine the cause of flaws before repairing so that procedure or design modifications can be made if necessary.

(3) Determine whether or not the flaw can or should be repaired; the repair weld is a heterogeneous area and as such may continue to function as a flaw.

(4) Remove entire flaw and prepare the joint area as in the original or modified procedure.

(5) Metal in the area to be repaired should be in the most suitable condition for making the repair.

(6) Make provisions for local or complete stress relief where necessary.

(7) If repairs must be made on material that has been given its final heat treatment, develop repair procedures on an experimental basis.

Much of the literature on the repair of joints in nickel-base alloys indicates the need for and successful accomplishment of repair welds in these alloys. Very little has been published on the details of the procedural changes required. This is taken as an indication

that, in many cases, successful repair is an art that depends on the skill and experience of the personnel involved.

Procedures have been described on one technique for repair welding René 41 (Ref. 25).

(1) Locally solution treat the required weld at 1950 F for 5 minutes

(2) Cold work the surface of the required weld by hammer peening at room temperature.

Both operations were performed before aging the required weld. The effect of hammer peening was to refine the grain size, and perhaps reduce residual stresses.

Three other repair-weld heat-treatment sequences for René 41 have been reported:

(1) Repair, solution treat, then use a double aging treatment, 1650/1400 F

(2) Repair, anneal at 1800 F, air cool, then age

(3) Repair, age, then furnace cool.

The particular attributes of these treatments were not given.

The repairability of René 41 on test assembly parts containing lap joints has been studied (Ref. 32). Attempts to make these repairs in the aged alloy were not successful when René 41 filler metal was used. Sound joints were obtained by using Hastelloy W filler metal. Manual welding was used. Synthetic defects were filled with weld metal while the heat input was gradually tapered off to produce suitable weld contours.

Tests on the repair welding of Astroloy showed that there was some difficulty in producing crack-free original welds in a restrained specimen (Ref. 25). By peening both immediately after welding and after solution treatment, suitable welds were made. Then, crack-free repair welds on the aged specimens were obtained by peening for 1 minute before reaging. Important considerations when repair welding age-hardenable alloys include (Ref. 90):

(1) Weld heat input
(2) Weld-backing media
(3) Filler-material selection
(4) Postweld heat treatments
(5) Special welding and grinding equipment.

Specially shaped furnaces for heating only those areas that have been repaired are used as a standard procedure for many repair welding applications.

Inconel 718 is a nickel-base high-strength alloy that can be repair welded with relatively little difficulty. Because of its particular age-hardening characteristics, Inconel 718 can be welded in the age-hardened condition and in more highly restrained conditions than other alloys.

Very little information is available concerning the repair of defective spot welds. A number of the defects classified as external defects can be repaired by very light machining of the external weld surfaces. The repair of cracked resistance welds must be accomplished by either a fusion-weld process or through the use of a mechanical fastener.

## CONCLUSIONS AND RECOMMENDATIONS

With few exceptions, nickel and nickel-base alloys are joined readily using conventional joining procedures. To prevent cracking, contamination of the weld joint and adjacent areas by foreign, potentially harmful materials must be avoided. Welded joints in some of the high-strength age-hardenable alloys are susceptible to cracking unless the base metal is in the proper condition of heat treatment prior to joining. The following recommendations are made to cover areas in which available information is limited or inadequate to completely solve the existing problems.

### CONTAMINATION

Many chemical elements that have harmful effects on welds in nickel-base alloys have been identified and remedies have been developed. However, as with other materials, there is a need to develop nondestructive techniques capable of detecting the presence of,

and possibly the amount of, foreign material present on surfaces in or near areas to be joined. Limits for cleanliness of the materials involved in joining also need to be established.

## WELDING METALLURGY

Additional information is needed on the welding metallurgy of some of the high-strength age-hardenable nickel-base alloys so that more satisfactory joining procedures and techniques can be developed. It is recommended that studies be undertaken to obtain the needed information. Studies of the effects of processing variables such as prior thermal and working history, welding thermal history, intermetallic reactions, and microstructures on joint properties should be included. A thorough knowledge of the welding metallurgy of these alloys will be useful in the development of filler metals and joining procedures and for preventing defects and contamination.

## WELDING CONDITIONS

Conditions for joining and related processing need to be extended for some alloys and processes. Useful information is limited on fabrication of nickel-base alloys by solid-state-joining techniques, plasma arc welding, electron-beam welding, and even MIG and resistance seam welding. Submerged-arc welding has limited applications for nickel-base alloys, partly because of the lack of suitable fluxes and filler metals. The additional development work that is needed would be determined by the material that is selected and by processes that are potentially useful.

## BRAZING

The brazing of nickel-base alloys has been studied extensively, but no completely satisfactory brazing filler metals have been developed for high-temperature applications of nickel-base alloys. Fluxes are needed for use where it is impractical to braze in controlled atmospheres. Prospects for developing more satisfactory filler metals and fluxes for the nickel-base alloys should be determined and, if favorable, followed with the required development programs.

## CRACKING

Methods for preventing fissuring or strain-age cracking in some nickel-base alloys need to be developed. Fissures in nickel-base-

alloy weldments often are considered to be potentially serious defects; their presence is prohibited for many nuclear, steam-power-plant, and aerospace applications. Strain-age cracking also presents a serious limitation to the use of some age-hardenable high-temperature nickel-base alloys. Additional research to study the causes and mechanisms of cracking would provide useful information needed to develop crack-prevention procedures. Indications are that such factors as prior thermal history, weld heat-input rates, and postweld heating procedures have important effects. However, overall solutions to the cracking problems are yet to be developed.

## REPAIR WELDING

Literature on repair of joints in nickel-base alloys indicates the need for improved repair-welding procedures. Available information on joint repairs is limited to repair procedures for arc-fusion welds by arc-fusion welding. Practically no published information is available on the repair of brazed joints or resistance spot or resistance seam welds. The development of repair procedures for and with other joining processes also needs to be considered, particularly with some of the high-strength age-hardenable nickel alloys. It appears that information on repair-welding procedures may contribute useful information for developing welding procedures after tack welding.

## TD NICKEL

TD nickel has some very desirable properties for high-temperature applications, and much work is in progress to develop suitable joining processes for this material. Difficulties when joining TD nickel appear to be related to agglomeration of thoria particles when the metal is melted and to delamination during or after welding. Studies aimed at developing methods for preventing delamination by procedure or material modifications might be worthwhile for this kind of material.

## DISSIMILAR METAL JOINING

It is often desirable to join one nickel-base alloy to a different nickel-base alloy or to a completely different material. Problems consequently arise in the proper choice of filler metal and from various heat treatments involved. A great amount of effort has been expended on such joints, but very little data are available in the

literature. A few filler-metal alloys have been developed for fusion welding dissimilar alloys, but even so the details of procedure and heat-treatment compromise are not often available. The acquiring of available data on joining of particular nickel-base alloys to other alloys, and the filling of the gaps in these data by experimental programs, would be worthwhile.

# APPENDIX

TABLE A-1. CROSS REFERENCE OF PRESENT AND PREVIOUS TRADE DESIGNATIONS FOR NICKEL AND NICKEL-BASE ALLOYS[a]

| DESIGNATION | PREVIOUS DESIGNATION |
|---|---|
| Nickel 200 | "A" Nickel |
| Nickel 201 | Low Carbon Nickel |
| Nickel 204 | Nickel 204 |
| Nickel 205 | "A" Nickel (electronic grade) |
| Nickel 211 | "D" Nickel |
| Nickel 212 | "E" Nickel |
| Nickel 220 | "220" Nickel |
| Nickel 225 | "225" Nickel |
| Nickel 230 | "230" Nickel |
| Nickel 233 | "330" Nickel |
| Nickel 270 | New Product |
| PERMANICKEL alloy 300 | PERMANICKEL alloy |
| DURANICKEL alloy 301 | DURANICKEL alloy |
| MONEL alloy 400 | MONEL alloy |
| MONEL alloy 401 | MONEL "401" alloy |
| MONEL alloy 402 | MONEL "402" alloy |
| MONEL alloy 403 | MONEL "403" alloy |
| MONEL alloy 404 | New Product |
| MONEL alloy R-405 | "R" MONEL alloy |
| MONEL alloy 406 | LC MONEL alloy |
| MONEL alloy K-500 | "K" MONEL alloy |
| MONEL alloy 501 | "KR" MONEL alloy |
| INCONEL alloy 600 | INCONEL alloy |
| INCONEL alloy 604 | INCONEL "600" alloy |
| INCONEL alloy 625 | New Product |
| INCONEL alloy 700 | INCONEL "700" alloy |
| INCONEL alloy 702 | INCONEL "702" alloy |
| INCONEL alloy 718 | INCONEL "718" alloy |
| INCONEL alloy 721 | INCONEL "M" alloy |
| INCONEL alloy 722 | INCONEL "W" alloy |
| INCONEL alloy X-750 | INCONEL "X" alloy |
| INCONEL alloy 751 | INCONEL "X-550" alloy |
| INCOLOY alloy 800 | INCOLOY alloy |
| INCOLOY alloy 801 | INCOLOY "T" alloy |
| INCOLOY alloy 804 | INCOLOY "804" alloy |
| INCOLOY alloy 805 | INCOLOY "805" alloy |
| NI-O-NEL alloy 825 | NI-O-NEL alloy |
| INCOLOY alloy 901 | INCOLOY "901" alloy |
| NI-SPAN-C alloy 902 | NI-SPAN-C alloy |
| NIMONIC alloy 75 | NIMONIC 75 alloy |
| NIMONIC alloy 80A | NIMONIC 80A alloy |

(a) From Handbook of Huntington Alloys, Huntington Alloy Products Division, The International Nickel Company, Inc., Huntington, West Virginia, Second Edition (May, 1963).

# REFERENCES


1. Dinsdale, W. O., "High-Temperature Fatigue Properties of Welded Joints in Heat Resisting Alloys", British Welding Journal, 12 (7), 344-348 (July, 1965) (RSIC 0952).

2. Evans, R. M., "Joining of Nickel-Base Alloys", DMIC Report 181, Defense Metals Information Center, Battelle Memorial Institute, Columbus, Ohio (December 20, 1962) (RSIC 0953).

3. Handbook of Huntington Alloys, Third Edition, Huntington Alloy Products Division, The International Nickel Company, Inc., Huntington, West Virginia, January, 1965 (RSIC 0682).

4. "TD Nickel Sheet – Dispersion Strengthened Nickel", Du Pont Metal Products, New Product Information, E. I. du Pont de Nemours & Company, Inc., Wilmington, Delaware (June, 1963) (RSIC 0944).

5. Simmons, W. F., "What Alloy Shall I Use for High-Temperature Applications (above 1200 F)?, Metal Progress, 78 (1), 84-91 (October, 1961) (RSIC 0117).

6. Pease, G. H., "The Practical Welding Metallurgy of Nickel and High-Nickel Alloys", Welding Journal, 36 (7), 330s-334s (July 1, 1957) (RSIC 0987).

7. Skelton, H. A., "Welding Stainless Steel and H T. Alloys", Canadian Metalworking, 21 (11), 38-46 (1958) (RSIC 0943).

8. Welding Handbook, Section 4, Fourth Edition, Chapter 67, "Nickel and High-Nickel Alloys", American Welding Society, New York, N. Y., pp 67.1-67.68, 1961 (RSIC 0954).

9. "Fusion Welding of Nickel and High-Nickel Alloys", Huntington Alloy Products Division, The International Nickel Company, Inc., Huntington, West Virginia, Technical Bulletin T-2 (January, 1962) (RSIC 0955).

10. Brazing Manual, American Welding Society, Inc., New York, N. Y., 1963 (RSIC 0956-0960).

11. Torgeson, D., "Welded Electronics Cleaning Requirements", Lockheed Missiles & Space Company, Sunnyvale, California, Report No. 3-26-62-1 (June, 1962) (RSIC 0942).

12. "Heating and Pickling Huntington Alloys", Huntington Alloy Products Division, The International Nickel Company, Inc. Huntington, West Virginia, Technical Bulletin T-20 (1962) (RSIC 0937).

13. "Pickling, Standard Process Specification", McDonnell Aircraft Corporation, St. Louis, Missouri, Specification No. P.S. 12050 (Issued January 31, 1950, Revision J, January 29, 1965) (RSIC 0676).

14. Schane, H. P. and Weismantel, E. G., "Fabrication Principle for Inconel X Structures", Welding Journal, 39 (11), 479s-483s (November, 1960) (RSIC 0936).

15. "Basic Data – Incoflux 4 Submerged Arc Welding Flux", Huntington Alloy Products Division, The International Nickel Company, Inc., Huntington, West Virginia (1964) (RSIC 0935).

16. "Basic Data – Incoflux 5 Submerged Arc Welding Flux", Huntington Alloy Products Division, The International Nickel Company, Inc., Huntington, West Virginia (1965) (RSIC 0934).

17. Christian, J. L., Yang, C. T., and Witzell, W. E., "Physical and Mechanical Properties of Pressure Vessel Material for Application in a Cryogenic Environment", General Dynamics/Astronautics, San Diego, California, Report No. GD/A 63-0818-3 (May 15, 1963, to May 15, 1965), Contract No. AF 33(657)-11289 (RSIC 0938).

18. Koppenhofer, R. L., Lewis, W. J., Faulkner, G. E., and Rieppel, P. J., "Development of Procedures For Welding 2-Inch-Thick Titanium Alloy Plate", Bimonthly Report to Bureau of Naval Weapons, Battelle Memorial Institute, Columbus, Ohio, Contract No. NOw-60-0390-C (October 31, 1960), DMIC 41417 (RSIC 0668).

19. Johnson, M. M. and Roseman, P., "Titanium Joins the Family of Commonly Used Metals", Welding Journal, 43 (4), 267-274 (April, 1964) (RSIC 0010).

20. Close, Gilbert C., "Transparent Welding Chamber Provides Cleanroom Conditions", Modern Machine Shop, 37 (3), 98-101 (August, 1964) (RSIC 0670).

21. Cary, H., "You Can Weld Titanium", Hobart Air Welding News AWN 177, Hobart Brothers Co., Hobart Square, Troy, Ohio, p 16 (Winter, 1965) (RSIC 0115).

22. Glasgal, B., "Development of Welding Procedures for Titanium Alloy Armor", Detroit Arsenal, Laboratories Division, Centerline, Michigan, Report No. 7594 (Final), 7 pp (RSIC 0023).

23. Glasgal, B. and Kalajian, Z., "Out-of-Chamber Welding of Thick Titanium", Welding Journal, 43 (5), 405-414 (May, 1964) (RSIC 0011).

24. Goodford, J. A. and Manfre, J. A., "Welding Titanium" (Brochure), Crucible Steel Company of American, 21 pp (RSIC 0666).

25. Lepkowski, W. J. Monroe, R. E., and Rieppel, P. J., "Studies on Repair Welding Age-Hardenable Nickel-Base Alloys", Welding Journal, 38 (9), 392s-400s (September, 1960) (RSIC 0939).

26. Spicer, K. M. and Pease, G. R., "Welding Inconel 'X'", TID 8015 (BMI-AEC Library) (March, 1958) (RSIC 0984).

27. "Heat Treating of Nickel and Nickel Alloy", Metals Handbook, Eighth Edition, Volume 2, American Society for Metals, Novelty, Ohio, pp 297-300 (1964) (RSIC 0964).

28. "The Electrada Corporation/Aerite Division" (Brochure), Los Angeles, California (undated) (RSIC 0963).

29. "Development of Joining Techniques for TD Nickel", General Electric Company, Cincinnati, Ohio, Interim Progress Report No. 3-8-211 (November 1, 1964, to February 1, 1965).

30. Claus, J., Meredith, D., and Sutch, F., "Manufacturing Methods for 'Hot Structures'", Boeing Airplane Company, Seattle, Washington, Technical Report 60-7-795, Section I. Volume II (December, 1960), Final Technical Engineering Report for USAF (June 1, 1959, to September 15, 1960), Contract No. AF 33(600)-39542 (RSIC 0680).

31. Cheever, D. C., Monroe, R. E., and Martin, D. C., "Mechanical Fastening of Nickel-Base Alloys", Unpublished report, Battelle Memorial Institute to Redstone Scientific Information Center, Redstone Arsenal, Alabama, Contract No. DA-01-021-AMC-11651(Z). (RSIC 0988).

32. Keith, R. E., Monroe, R. E., and Martin, D. C., "Adhesive Bonding of Nickel and Nickel-Base Alloys", Unpublished report, Battelle Memorial Institute to Redstone Scientific Information Center, Redstone Arsenal, Alabama, Contract No. DA-01-021-AMC-11651(Z) (RSIC 0989).

33. Welding Handbook, Section 2, Fifth Edition, Chapter 25, "Shielded-Metal-Arc Welding, Principles of Operation", American Welding Society, New York, N. Y., pp 25.2-25.3, 1963 (RSIC 0949).

34. Slaughter, G. M., Welding and Brazing Techniques for Nuclear Reactor Components, AEC Monograph, Rowman and Littlefield, New York, N. Y., 1964, Chapter 4, "Pressure and Containment Vessels, Inconel", pp 101-104; Chapter 6, "Piping, Inconel", pp 156-160 (RSIC 0948 and 0950).

35. "Tentative Specification for Nickel and Nickel-Alloy Covered Welding Electrodes", American Welding Society, AWS 5.11-64T, American Society for Testing and Materials ASTM B295-64T, New York, New York (Issued 1954, Revised 1964) (RSIC 0947).

36. Witherell, C. E., "Welding of Nickel-Chromium-Iron Alloy for Nuclear Power Stations", Welding Journal, 39 (11), 473s-478s (November, 1960) (RSIC 0946).

37. "Hastelloy High-Strength, Nickel-Base, Corrosion-Resistant Alloys", Haynes Stellite Company, Kokomo, Indiana (September 1, 1951) (RSIC 0951).

38. Welding Handbook, Section 2, Fifth Edition, Chapter 27, "Gas-Shielded Arc Welding, Fundamentals of Process", pp 27.2-27.4 1963 (RSIC 0945).

39. "Tentative Specifications for Tungsten-Arc Welding Electrodes", AWS Designation A5.12-55T, American Welding Society, New York, N. Y. (1955) (RSIC 0796).

40. "Tentative Specification for Nickel and Nickel-Alloy-Base Welding Rods and Electrodes", American Welding Society, AWS A5.14-64T, American Society for Testing and Materials, ASTM B304-64T, New York, New York (Issued 1956, Revised 1964) (RSIC 0981).

41. Huebner, J., "Inconel X Weldments, Special Heat Treating", McDonnell Aircraft Corporation, St. Louis, Missouri, Final Report No. A066 (April 2, 1963) (RSIC 0969).

42. Alesch, C. W., "Material-Nickel-Base Alloy Hastelloy R235, Fusion Weld Strengths", General Dynamics/Convair, San Diego, California, Report No. 8926-171 (April 19, 1963) (RSIC 0968).

43. O'Connell, J. F., Ritchey, N. J., and Stewart, J. C., "Corrugated Monel Heat Exchanger", Welding Journal, 40 (9), 934-941 (September, 1961), (RSIC 0967).

44. "How Nickel Helps Hooker to Fight Corrosion Cracking Down on Cracker Crack-Up", Huntington Alloy Products Division, The International Nickel Company, Inc., Huntington, West Virginia, Process Industries Quarterly, 21 (2) p 4 (undated) (RSIC 0966).

45. Heath, D. J. and Thorneycraft, D. R., "Pipe Welding Techniques for Nickel Containing Materials", Welding and Metal Fabrication, 33 (2), 44-56 (February, 1965) (RSIC 0982).

46. Rabensteine, A. S., "Selected Mechanical Properties of Hastelloy C Alloy Plate (0.250 inch) and Forging", The Marquardt Corp., Van Nuys, California, Report PR 281-2Q-2 (December 1, 1962), Contract No. AF 33(657)-8706 (RSIC 0983).

47. Welding Handbook, Section 2, Fifth Edition, Chapter 28, "Submerged Arc Welding", American Welding Society, New York, New York, pp 28.2-28.15, 1963 (RSIC 0985).

48. Duhamel, R. F., Schaper, C. D., and Schollhammer, F. R., "Final Report on Nonvacuum Electron-Beam Welding", Hamilton Standard Division, United Aircraft Corporation, Windsor Rocks, Connecticut, Final Report No. AFML-TR-65-11 on Contract No. AF 33(615)-1052 (November, 1964) (RSIC 0986).

49. "Electron-Beam Welds Salvage Costly Rejects", Metalworking, 18, 24-25 (May, 1962) (RSIC 0802).

50. White, S. S., Lander, H. J., Hess, W. T., and Bakish, R., "A Study of Electron-Beam Welding", Welding Journal, 41 (6), 279s-288s (June, 1962) (RSIC 0757).

51. Kern, W. I. and Lubin, L. E., "Electron-Beam Welding of Aerospace Materials", Hamilton Standard Division, United Aircraft Corporation, Windsor Locks, Connecticut, Final Report No. ASD-TDR-63-132 (February, 1963) (RSIC 0800).

52. White, H., "Rolls-Royce Puts Electron Beams to Work", Metalworking Production, 103, 85-87 (June 13, 1962) (RSIC 0645).

53. Personal communication from R. Avery, Huntington Alloy Products Division, The International Nickel Company, Inc., Huntington, West Virginia (July 8, 1965) (RSIC 0962).

54. Filipski, S. P., "Plasma Arc Welding, Welding Journal, 43 (11), 937-943 (November, 1964) (RSIC 0755).

55. O'Brien, R. L., "Plasma-Arc Welding Applications", American Society for Metals, Novelty, Ohio, Technical Report No. P (January 1, 1964) (RSIC 0644).

56. Personal communication with Stanley Filipski, Linde Division, Union Carbide Corporation, Newark, New Jersey (August 11, 1965) (RSIC 0874).

57. Stratton, W. K., "Advances in the Materials Technology Resulting from the X-20 Program", "Superalloys", Part I, Section V, The Boeing Company, Seattle, Washington, Technical Report No. AMFL-TR-64-396 (December, 1964) (RSIC 0961).

58. Crane, C. H., "Resistance Welding Super Alloys", The Boeing Company, Seattle, Washington, Report No. D2-80278 (Preparation date: January 10, 1964) (RSIC 0916).

59. "Resistance Welding of Nickel and Nickel-Base Alloys", Huntington Alloy Products Division, The International Nickel Company, Inc., Huntington, West Virginia, Technical Bulletin T-33 (September, 1959) (RSIC 0976).

60. Nippes, E. F., and Fishman, H. B., "Optimum Spot and Seam Welding Conditions for Inconel 'X'", Welding Journal, 34 (1), 1s-14s (1954) (RSIC 0977).

61. "Welding: Aluminum, Magnesium, Non-Hardening Steels or Alloys, and Titanium, Spot, Seam and Stitch", Military Specification MIL-W-6858B (RSIC 0798).

62. Huebner, J., "Reaging of Inconel 'X' Sheet-Effect on Fatigue Properties", McDonnell Aircraft Corporation, St. Louis, Missouri, Report No. 032-998.01 (August 8, 1963) (RSIC 0978).

63. "Processing and Materials Review for Aircraft Design Manual", Report No. ARDL-TR-56-7, Part I, A. O. Smith Corporation, Aeronautical Division, Milwaukee, Wisconsin, Contract No. AF 18(600)-1513, (Date not reported) (RSIC 0512).

64. "Development of Joining Techniques for TD-Nickel", General Electric Company, Cincinnati, Ohio, Interim Progress Report No. 2-8-211 (August 1, 1964, to October 31, 1964) (RSIC 0970).

65. Rings, "American Welding and Manufacturing Company" (Brochure), Warren, Ohio (RSIC 0979).

66. Bates, T. T. and Manning, C. R., Jr., "A Preliminary Study of the Solid-State Bonding of Thoria Dispersion Strengthened Nickel", NASA Langley Research Center, Langley Station, Hampton, Virginia, Presented at the Eighth Meeting of the Refractory Composites Working Group, Fort Worth, Texas (January 14-16, 1964) (RSIC 0980).

67. Davies, R.J.N. and Stephenson, N., "Diffusion Bonding and Pressure Brazing of Nimonic 90, Ni-W-Co Alloy", British Welding Journal, 90 (3), 139-148 (1962) (RSIC 0971).

68. Metcalfe, A. G., "Modern Diffusion Bonding Meets Space Age Needs", SAE Journal, 72 (4), 53-57 (1964) (RSIC 0972).

69. Metcalfe, A. G., et al., "Diffusion Bonding of Refractory Metals", Solar, Contract No. AF 33(657)-8789, Progress Reports 1 through 7 (RSIC 0930-0933 and 0973-0975).

70. Bartlett, E. S. and Ogden, H. R., "Summary of the Eighth Meeting of the Refractory Composites Group", Defense Metals Information Center, Battelle Memorial Institute, Columbus, Ohio, DMIC Memorandum 192, p 12 (1964) (RSIC 0929).

71. Bianchi, L. M., "Fabricating Under an Inert Atmosphere", Metal Progress, 87 (3), 127-131 (March, 1965) (RSIC 0750).

72. Jaffee, R. I., "Method of Producing Ribbed Metal Sandwich Structures", U. S. Patent 3,044,160 (Filed March 3, 1958) (RSIC 0500).

73. Leach, J. E., Jr., "Diffusion Bonding of Structures by Hot-Rolling Plate Mill Techniques', Douglas Missile and Space Systems Division Paper No. 3207 (October, 1964) (RSIC 0678).

74. "Roll-Welded Structures", Douglas Aircraft Company, Battelle Memorial Institute, Columbus, Ohio (November, 1963) (RSIC 0940).

75. Lage, A. P., "Pressure Vessel Fabrication", Paper presented at SAE Aerospace Manufacturing Forum, Los Angeles, California (October 5, 1964) (RSIC 0941).

76. Welding Handbook, Section 2, Fifth Edition, Chapter 22, "Pressure Gas Welding", American Welding Society, New York, New York, pp 22.1-22.22, 1963 (RSIC 0870).

77. Lage, A. P., "Application of Pressure Welding to the Aircraft Industry", Revision of a paper presented at the 1956 AWS National Spring Meeting in Buffalo, New York, May 7-11, 1956, Menasco Manufacturing Company, Burbank, California (Revised February, 1959) (RSIC 0178).

78. Personal communication with Summer Smith, Menasco Manufacturing Company, Burbank, California (August 10, 1964) (RSIC 0873).

79. Barker, I. F., Mobley, P. R., and Redden, T. K., "A New Brazing Alloy for Age-Hardenable Super Alloys", Welding Journal, 41 (9) 409s-412s (1962) (RSIC 0921).

80. "Brazing and Soldering Huntington Alloys", Huntington Alloy Products Division, The International Nickel Company, Inc., Huntington, West Virginia, Technical Bulletin T. 34 (February, 1962) (RSIC 0923).

81. Hoppin, G. S., III, and Bamberger, E. N., "Effects of Hydrogen Brazing on Properties of High-Temperature Alloys", Welding Journal, 38 (4), 194s-200s (RSIC 0922).

82. Sinclair, J. H. and Gyorgak, C. A., "Effects of Two Braze Coatings, Processing Variables and Heat Treatments on 1200 F Stress Rupture Strength of L-605, A-286, and Inconel 700 Sheet", NASA Technical Note WASA TN D-1880, Lewis Research Center, National Aeronautics and Space Administration (November, 1963) (RSIC 0924).

83. Wilson, R. M. and Burchfield, W. F., "Nickel and High Nickel Alloys for Pressure Vessels", Welding Journal, 35 (1), 32s-40s (January, 1956) (RSIC 0920).

84. Bland, J. and Owczarski, W. A., "Arc Welding of Ni-Cr-Fe (Inconel) Alloy for Nuclear Power Plants, The American Society of Mechanical Engineers Paper for presentation at the ASME-AWS Metals Engineering Conference, Los Angeles, California (April 25-29, 1960) (RSIC 0925).

85. Fragetta, W. A. and Pease, G. R., "The Welding of Inconel for Nuclear-Power Amplifications", Welding Journal, 38 (4), 347-356 (1959) (RSIC 0919).

86. Johnson, C., "Welding Hastelloy Alloy X to Inconel and to Mild Steel", Welding Design and Fabrication, 32 (2), 40-42 (1959) (RSIC 0918).

87. Cordea, J. N., Kammer, P. A., and Martin, D. C., "Causes of Fissuring in Nickel-Base and Stainless Steel Alloy Weld Metals", Welding Journal, 43 (11), pp 481s-491s (November, 1964) (RSIC 0926).

88. Blum, B. S., Shaw, P., and Wickesser, A., "Improved Methods for Welding Age-Hardenable High-Temperature Alloys", Republic Aviation Corporation, Farmingdale, New York, Report No. ASD-TDR-63-601, Contract No. AF 33(616)-7670 (June, 1963) (RSIC 0927).

89. "Seam Welding Defects in Austenitic Stainless", Engineering Data Sheet No. 281, Welding Engineer (January, 1964) (RSIC 0917).

90. Weiss, S. and Hacker, D. E., "The Fabrication of High Thrust Lightweight Jet Engines", 1961 SAE National Aeronautic Meeting, 340 F, New York, New York (1961) (RSIC 0928).

APPROVAL

NASA TM X-53447

JOINING OF NICKEL AND NICKEL-BASE ALLOYS

By J. J. Vagi, R. E. Monroe, R. M. Evans, and D. C. Martin

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

RH W. A. Wilson

W. A. WILSON
Chief, Methods Development Branch

J. P. Orr

J. P. ORR
Chief, Manufacturing Research and Technology Division

for WERNER R. KUERS
Director, Manufacturing Engineering Laboratory